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Stratigraphy of the Sauk III Interval (Cambrian-Ordovician) in the Ibex Area, Western Millard County, Utah and Central Texas

JAMES F. MILLER and KEVIN R. EVANS
Department of Geography, Geology, and Planning, Southwest Missouri State University, Springfield, Missouri 65804

JAMES D. LOCH
Earth Sciences Department, Central Missouri State University, Warrensburg, Missouri 64093

RAYMOND L. ETHINGTON and JAMES H. STITT*
Department of Geological Sciences, University of Missouri-Columbia, Columbia, Missouri 65211

LARS HOLMER
Institute of Earth Sciences, Historical Geology, and Palaeontology, Uppsala University, S-752 36 Uppsala, Sweden

LEONID E. POPOV
Department of Geology, National Museum of Wales, Cathays Park, Cardiff CF10 3NP, Wales, United Kingdom

ABSTRACT

Lithostratigraphic and biostratigraphic data support a new model for the sequence stratigraphy of the Sauk III interval in Utah. The Steamboat Pass Shale and Sneakover Limestone members of the Orr Formation and most of the Notch Peak Formation comprise the Millardan Series (upper Cambrian). The uppermost Notch Peak Formation and the House Limestone together constitute the Skullrockian Stage of the Ibexian Series (lower Ordovician). These Millardan, Ibexian, and Skullrockian strata have their type areas in the Ibex area of Millard County, Utah. These strata are ca. 2700 feet (ca. 825 m) thick in the northern Wah Wah Mountains, in the House Range and adjacent Tule Valley, and in the northern Drum Mountains. Seventeen sections were measured in three local tectonic elements, the Wah Wah Arch (new) on the south, the House Range Embayment, and the Tooele Arch in the north. These tectonic elements influenced thickness and lithofacies patterns during deposition of Cambrian-Ordovician strata. The transition between the House Range Embayment and the Wah Wah Arch is located slightly north of Skull Rock Pass in the central House Range.

The timing and correlation of the new sequence framework is based on conodonts, trilobites, and brachiopods. Most of the Notch Peak and all of the House have abundant conodont faunas that are assigned to these previously established zones: *Proconodontus tenuiserratus, P. posterocostatus, P. muelleri, Eoconodontus* (with *Eoconodontus notchpeakensis* and *Cambrooistodus minutus* subzones), *Cordylodus proavus* (with *Hirsutodontus hirsutus, Fryxellodontus inornatus,* and *Clavohamulus elongatus* subzones), *Cordylodus intermedius* (with *Hirsutodontus simplex* and *Clavohamulus hintzei* subzones), *Cordylodus lindstromi* sensu lato, *Iapetognathus, Cordylodus angulatus,* and *Rossodus manitouensis.* The *Cordylodus lindstromi* sensu lato Zone is divided herein into Lower and Upper subzones, and the *Rossodus manitouensis* Zone is divided herein into a lower, thin *Loxodus bransoni* Subzone and an upper, thick *"Paltodus" spurius* Subzone. Another conodont biozonal unit, the Low Diversity Interval, is in the lowest part of the overlying Fillmore Formation.

Trilobites are known from most of the stratigraphic interval. The Steamboat Pass Shale and Sneakover Limestone members of the Orr Formation have trilobites that have been assigned previously to the *Elvinia* Zone.

*Deceased September, 1999

The lower part of the Hellnmaria Member has one trilobite collection assigned to the *Taenicephalus* Zone. The middle part of the Hellnmaria Member has one trilobite collection assigned to the *Saratogia* Zone. The uppermost Hellnmaria Member through the House Limestone have been assigned to the following previously established zones: *Saukia* (with *Saukiella pyrene, Saukiella junia,* and *Saukiella serotina* subzones), *Missisquoia* (with *M. depressa* and *M. typicalis* subzones), *Symphysurina, Bellefontia,* and *Paraplethopeltis.* The top 9 feet (2.7 m) of the House Limestone and the lower beds of the Fillmore Formation are assigned to the *Leiostegium-Kainella* Zone. The *Symphysurina* Zone is divided into the *Symphysurina brevispicata, S. bulbosa,* and *S. woosteri* subzones. The widespread olenid trilobite *Jujuyaspis borealis* occurs in six sections in the Ibex area at or <1 m above the base of the *S. bulbosa* Subzone; it is an indicator of the base of the traditional Tremadocian Series of the Acado-Baltic Faunal Province.

Organophosphatic brachiopods are present in large numbers in these strata; calcitic brachiopods are less abundant. Brachiopods are useful for correlation, but no zonation is established in these strata. Two previously established zones, the *Apsotreta* and *Linnarssonella* zones, are recognized in the Steamboat Pass Shale Member and in the coeval Corset Spring Shale Member of the Orr Formation.

Sauk III strata are divided into 13 sequences, beginning with a karst surface in the Steamboat Mountain Shale Member and in the coeval Corset Spring Member of the Orr Formation. This karst surface is in the lower part of the *Elvinia* Zone and is the boundary between the Sauk II and Sauk III intervals. Sequence 1 occurs in the upper members of the Orr Formation and in the lower part of the Hellnmaria Member of the Notch Peak Formation. Sequences 2 to 4 comprise the remainder of the Hellnmaria Member. The base of Sequence 4 is a widespread karst surface. Sequences 5 to 9 comprise the Red Tops and Lava Dam members of the Notch Peak Formation. Sequences 10 and 11 encompass the Barn Canyon Member and lower Burnout Canyon Member of the House Limestone. Sequence 12 constitutes the upper Burnout Canyon Member and most of the Red Canyon Member of the House Limestone. Sequence 13 includes the top beds of the Red Canyon Member and the basal beds of the Fillmore Formation. Sequence 14 is in the lower part of the Fillmore Formation. Some of these sequences are separated by discrete truncation surfaces that are demonstrably unconformable. Variations in the concentration of insoluble residues, consisting mostly of fine quartz sand, are also important in delineating and characterizing these sequences. Most of these sequences are divided into smaller parts, referred to by the generic term "packages" to avoid confusion with terms such as "parasequences" or "parasequence sets."

Rapid subsidence of the miogeoclinal carbonate platform produced sufficient accommodation for preservation of strata deposited during lowstands of sea level. Seven main intervals of lowstand strata are recognized, the Corset Spring Lowstand (strata below and including the lower part of Sequence 1), Red Tops Lowstand (lower part of Sequence 5), Lange Ranch Lowstand (top of Sequence 6 and all of Sequence 7), Basal House Lowstand (base of Sequence 10), Drum Mountains Lowstand (base of Sequence 11), Burnout Canyon Lowstand (top of Sequence 11 and lower part of Sequence 12), and Tule Valley Lowstand (Sequence 13 and lower part of Sequence 14). Two major transgressive intervals are recognized, the Sauk III Transgression (lower part of Sequence 1) and the Stonehenge Transgression (second through sixth packages of Sequence 11). Most of the Hellnmaria Member represents a period of generally high sea level conditions that is named the Hellnmaria Highstand.

These sequences, packages, lowstands, highstands, and transgressive intervals are characterized by precise conodont and trilobite biostratigraphy and can be recognized in central Texas, and they have potential to be correlated with similar successions in other areas of the world.

Important chronostratigraphic boundaries can be tied into the 14 sequences. The base of the Sunwaptan Stage is in the lower part of Sequence 1. The base of the Ibexian Series and its Skullrockian Stage is near the top of Sequence 6. The base of the Canadian Series is in Sequence 7. The base of the traditional Tremadocian Series of the Acado-Baltic Faunal Province is in the lower part of Sequence 11. The base of the Stairsian Stage is in Sequence 13. The base of the Ordovician System at the global stratotype at Green Point, Newfoundland, is within strata containing a redeposited and inverted conodont faunal succession, so that boundary cannot be correlated confidently with the Utah succession. However, we speculate that it must be at some horizon within Sequence 11.

INTRODUCTION

Strata in the Ibex area of western Millard County, Utah constitute the type area for the uppermost Cambrian and the lowermost Ordovician series in North America. Palmer (1998) divided the Cambrian System into four series, of which the youngest is the Millardan Series, named for exposures in Millard County, Utah. Palmer divided the Millardan into two stages, the lower Steptoean Stage and the upper Sunwaptan Stage. The Steptoean Stage in the type area of the Millardan Series is part of the Orr Formation. The Sunwaptan Stage in the type area of the Millardan Series consists of strata assigned to the uppermost Orr Formation and most of the Notch Peak Formation. Ross et al. (1997) assigned the top strata of the Notch Peak Formation and all of the overlying House Limestone to the Ibexian Series, the lowest of four series of the Ordovician System in North America. The Ibexian was named for exposures near the former homestead of Ibex in an uninhabited part of Millard County that residents refer to as the "West Desert" (Fig. 1). These top strata of the Notch Peak and all but the top 9 ft (2.7 m) of the House Limestone constitute the Skullrockian Stage, the lowest of four stages in the Ibexian Series. The younger Stairsian Stage includes the uppermost strata of the House and part of the overlying Fillmore Formation.

The lithostratigraphy of these strata is well known. The Orr Formation has several members that were discussed by Hintze and Palmer (1976). In the central House Range these members are the Big Horse Limestone (lowest), Candland Shale, Johns Wash Limestone, Corset Springs Shale, and Sneakover Limestone (highest). In the southern House Range a single unit, the Steamboat Pass Shale Member, occurs between the Big Horse and Sneakover Limestone members. Some of these units are shown on Figure 2. Hintze et al. (1988) divided the Notch Peak Formation into the Hellnmaria (lower), Red Tops (middle), and Lava Dam (upper) members, which are shown on Figures 2 and 3. Miller et al. (2001) discussed the lithostratigraphy of these strata and named two thin marker beds, the Tank Canyon Bed and the Lawson Cove Bed, near the middle of the Lava Dam Member. Those authors also divided the overlying House Limestone into the Barn Canyon (lower), Burnout Canyon (middle), and Red Canyon (upper) members. These stratigraphic units are summarized on Figure 3 and Table 1 (CD-ROM). Popov et al. (2002) described organophosphatic brachiopods from Notch Peak and House strata. Studies of brachiopods from other parts of the Millardan and Ibexian are in progress by the same authors.

This report is part of a comprehensive documentation of strata that comprise the upper Millardan and lower Ibexian series, including most of the Sunwaptan Stage, all of the Skullrockian Stage, and the lowest part of the overlying Stairsian Stage. The stratigraphy of the Fillmore Formation is the focus of a separate research project (Dattilo et al., 2001). These strata have been mapped at a scale of 1:100,000 by Hintze and Davis (2002a, 2002b).

This report integrates diverse kinds of stratigraphic information, including lithostratigraphic, biostratigraphic, sequence stratigraphic, and chronostratigraphic data through an interval of approximately 2700 feet (825 m). Exceptional amounts of diverse data are available from 17 measured sections. Miller et al. (2001) presented descriptions of five of the sections located on Figure 1 (A, B, D, E, R). Herein we reproduce these descriptions and include descriptions of 12 additional sections, all of which are on the accompanying CD-ROM. All of the sections are measured in five-foot (ca. 1.5-m) increments and are marked with yellow paint. Range charts of conodonts, trilobites, and brachiopods from some of these sections document the conodont and trilobite biozonations used to correlate strata.

The principal goal of this report is to document a detailed sequence stratigraphy that is based primarily on sections in the Ibex area, although we include detailed correlations to sections in central Texas. We also discuss the correlation potential of the stratotype section for the base of the Ordovician System at Green Point in Newfoundland, Canada.

TECTONIC SETTING

J. F. Miller and K. R. Evans

Local and regional tectonic elements influenced deposition and lithofacies variation in Cambrian and Ordovician strata of the Ibex area. Two major regional tectonic elements are the Transcontinental Arch, a cratonic high in central to western Colorado, and the miogeocline that existed on the western margin of Laurentia. This miogeocline formed in late Proterozoic time by continental rifting, which was followed by rapid subsidence of a tropical carbonate platform that developed in eastern Nevada and western Utah. Cambrian strata exposed in the House Range area are ca. 10,000 feet (3050 m) thick, but the base of the succession is covered. Ordovician strata in the same general area are ca. 5000 feet (1525 m) thick. Rapid subsidence of the miogeocline produced accommodation that resulted in a Lower Cambrian to Lower Triassic succession of ca. 32,000 feet (9.8 km) of mostly carbonate strata that includes few significant unconformities.

Several local shelf-normal tectonic elements (Fig. 1) had a more direct effect on facies changes recorded in these strata. North of the House Range-Ibex area was the Tooele Arch, a positive tectonic element described and figured by Hintze (1988, Fig. 26). Strata in the northern Drum Mountains (Fig. 1) were deposited on the south flank of the Tooele Arch. Rees (1986) discussed the House

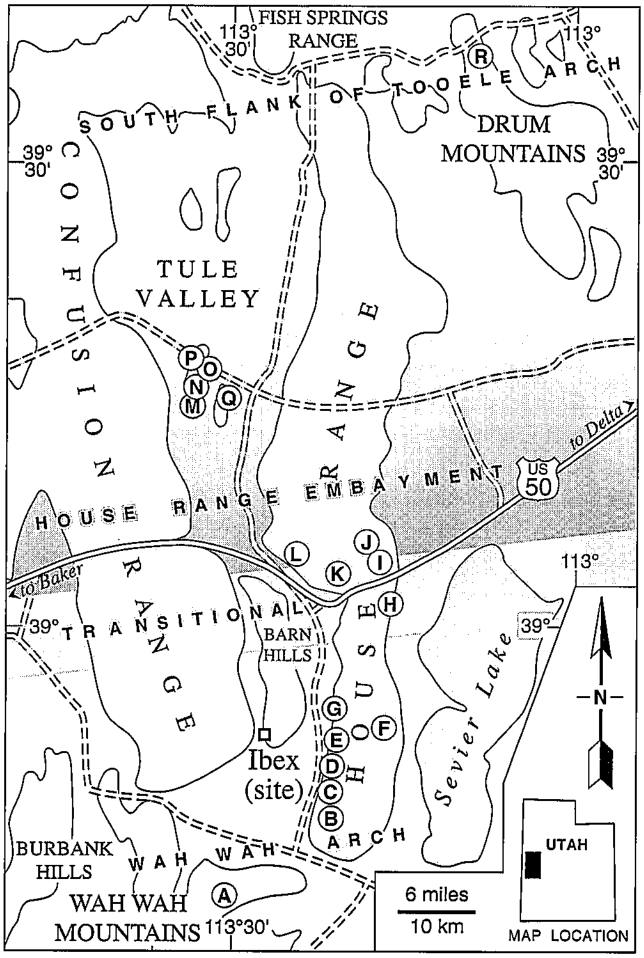


Figure 1. Location map showing measured sections and tectonic elements that affected lithofacies distribution. A = Lawson Cove. B = Steamboat Pass. C = Lava Dam South (little used). D = Lava Dam Five. E = Lava Dam North. F = Sevier Lake. G = 1965 C section. H = Sevier Lake Corral. I = Tank Canyon. J = Sneakover Pass. K = Notch Peak section (little used). L = Section A. M = Chalk Knolls South. N = Chalk Knolls Middle. O = Chalk Knolls North. P = original Chalk Knolls section (now abandoned). Q = East Shoreline Butte. R = Drum Mountains section. Sections A–G were deposited on the Wah Wah Arch, a new tectonic element named herein. Sections H,I,K are in a transition zone between the Wah Wah Arch and the House Range Embayment. Sections J, L–Q were deposited in the House Range Embayment, a subsiding tectonic element. Section R was deposited on the south flank of the Tooele Arch, an area of uplift that was mostly farther north.

Range Embayment and its influence on Middle Cambrian sedimentation across the miogeocline. She interpreted this tectonic feature to be an embayment of deep-water facies into the shallow-water miogeocline along the western margin of Laurentia. This embayment trended NE-SW across Nevada and western Utah, was fault-bounded on the south, and shallowed into a ramp northward. The southern margin of the House Range Embayment may have been a Cambrian-Ordovician growth fault. Rees studied Middle Cambrian exposures at the south end of the House Range (slightly south of location B on Fig. 1), and she determined that these strata were deposited south of the embayment on a shallow shelf. She concluded that exposures in the Marjum Pass-Antelope Springs area in the central House Range (middle part of Fig. 1 herein) formed north of the boundary fault, within the House Range Embayment. Middle Cambrian strata are not exposed between these two areas, so Rees could not locate the south margin of the embayment more precisely. Exposures of the Notch Peak and House formations occur between these two areas, so it is possible to locate the southern margin of the House Range Embayment in greater detail. Facies changes within these exposures suggest that sections at locations A–G on Figure 1 were deposited on the southern shelf identified by Rees (1986), and sections at locations J, L, and M–Q were deposited in the House Range Embayment. Sections at locations H, I, and K appear to form a transition zone between the shelf and embayment tectonic settings; these sections are near Skull Rock Pass, where U.S. Highway 6–50 crosses the House Range.

Herein we introduce the new name "Wah Wah Arch" for this positive area south of the House Range Embayment. This tectonic feature extends southwestward into Nevada. Southwest of the Wah Wah Arch is another basin in Nevada.

LITHOFACIES

J. F. Miller and K. R. Evans

Notch Peak, House, and basal Fillmore strata in the Ibex area comprise a succession of interbedded clean carbonates, carbonates with usually minor admixtures of fine to coarse quartz sand, cherty carbonates, and shale, with minor sandstone, evaporites, and conglomerate. The stratigraphic succession is documented in section descriptions on the accompanying CD-ROM. We do not propose depth parameters for most of the common carbonate lithologies. However, Osleger and Reed (1993, Table 1) did estimate water depths for different lithologies recognized in strata that they studied. Some of the same strata were studied in both of our reports, and their estimates may be applied to strata we discuss herein.

Principal lithologies that we recognize include: 1) laminated carbonate mudstone, 2) burrowed carbonate mudstone to wackestone, 3) fine peloid grainstone, 4) peloid grainstone, 5) trilobite grainstone to wackestone, 6) ooid grainstone, 7) intraclast grainstone, 8) flat-pebble and edgewise limestone conglomerate, 9) laminated sandy fine grainstone with cross-laminated sets, 10) stromatolitic bioherms

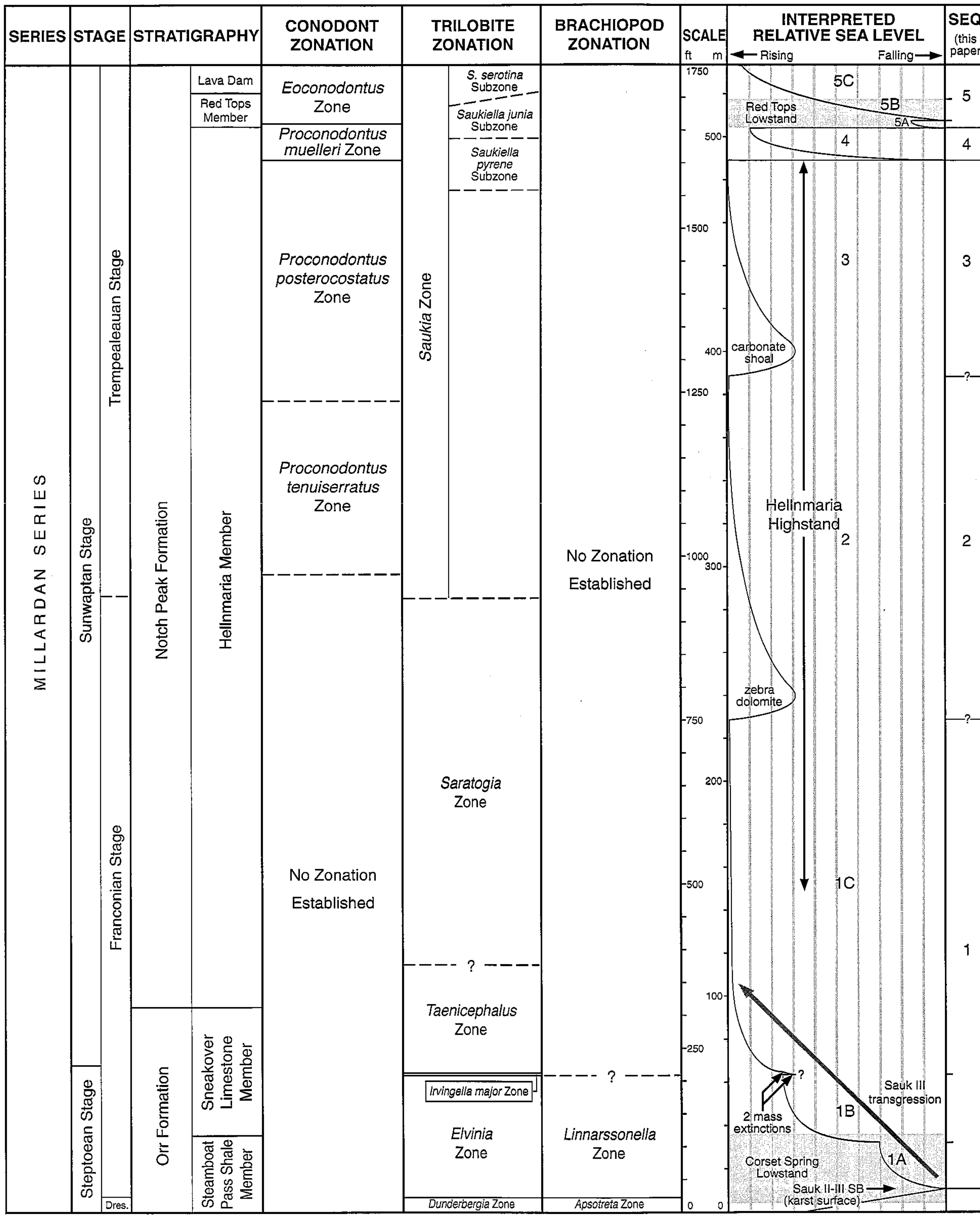


Figure 2. Chronostratigraphic, lithostratigraphic, biostratigraphic, and sequence stratigraphic units for the lower part of the interval studied, the upper members of the Orr Formation and the lower members of the Notch Peak Formation. Curve shows inferred changes in relative sea level. Dres. = Dresbachian Stage. SEQ. = sequences discussed in text. Thicknesses of units based on Lawson Cove Reservoir section of Hintze and Palmer (1976) for Orr Formation and Hintze et al. (1988) for Notch Peak Formation.

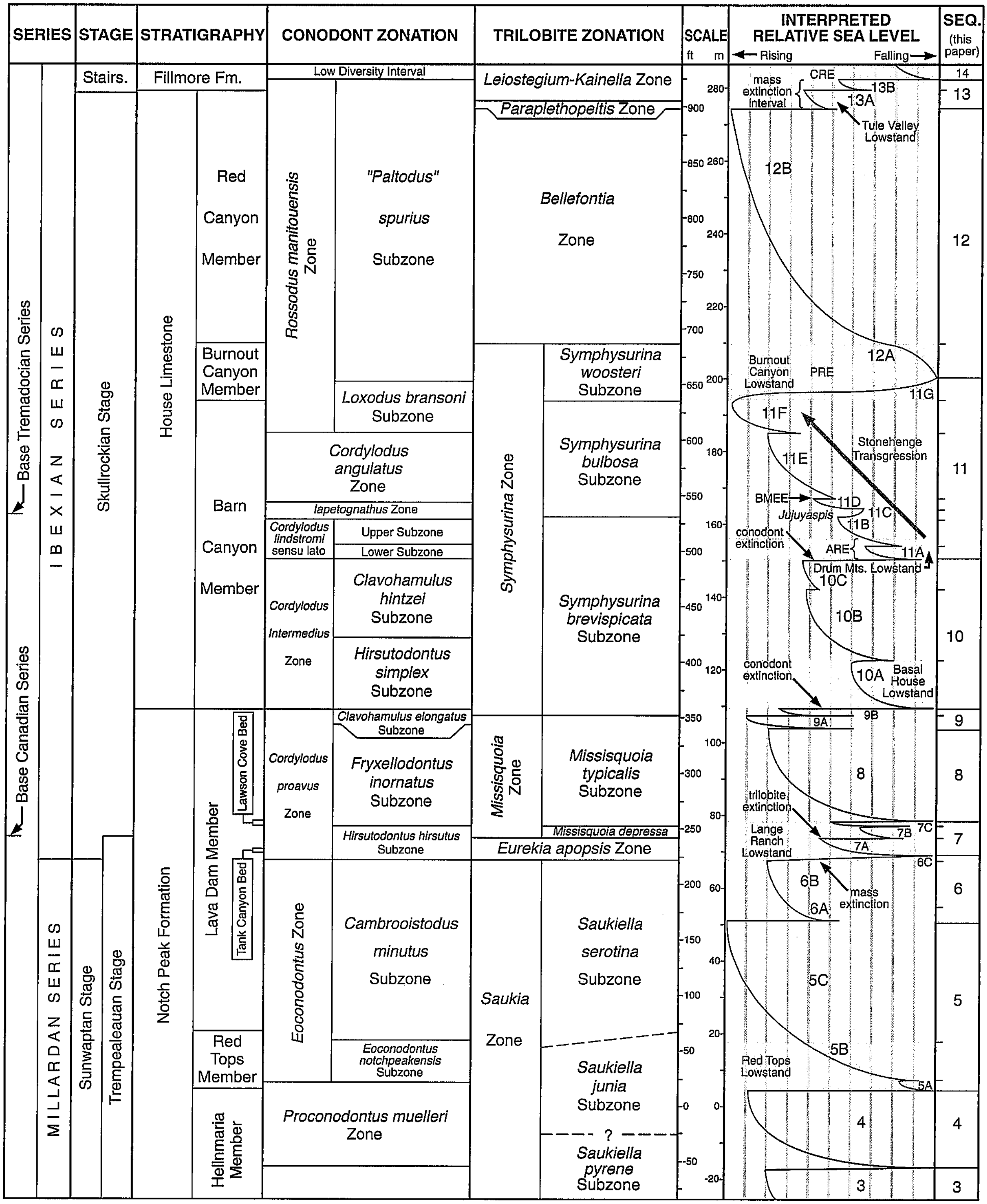


Figure 3. Chronostratigraphic, lithostratigraphic, biostratigraphic, and sequence stratigraphic units for the upper part of the interval studied, the upper members of the Notch Peak Formation, members of the House Limestone, and the lowest part of the Fillmore Formation. Curve shows inferred changes in relative sea level. Stairs. = Stairsian Stage. SEQ. = sequences discussed in text. ARE = Acerocare *Regressive Event. BMEE = Black Mountain Eustatic Event. PRE =* Peltocare *Regressive Event. CRE =* Ceratopyge *Regressive Event. Thicknesses of units based on Steamboat Pass, Lawson Cove, Lava Dam North, and 1965 C sections.*

and biostromes, 11) thrombolitic bioherms, 12) oncoid grainstone, 13) chert, 14) dolomite, 15) zebra-rock dolomite, 16) shale, 17) quartz sandstone, 18) evaporite minerals, and 19) chert-clast conglomerate.

We interpret these lithologies as representing a variety of marine depositional environments. Lithology 1, laminated carbonate mudstone, is the deepest marine deposit found in these strata and was deposited below storm wave base. Lithology 2, burrowed carbonate mudstone to wackestone, is a relatively deep subtidal marine deposit, generally deposited below fair-weather wave base. Lithology 3 (fine peloid grainstone), 4 (peloid grainstone), and 5 (trilobite grainstone to wackestone), are shallow subtidal deposits influenced to varying degrees by currents. Lithology 6, ooid grainstone, is a shallow subtidal deposit strongly affected by tidal currents. Lithology 7 (intraclastic grainstone) and 8 (flat-pebble and edgewise limestone conglomerate) are shallow subtidal deposits strongly influenced by tidal and storm currents. Lithology 9, laminated sandy fine grainstone with cross-laminated sets, is a peritidal to tidal-flat deposit that was strongly influenced by tidal currents. Lithology 10 (stromatolitic bioherms and biostromes) and 11 (thrombolitic bioherms) may not represent a single depositional environment. Most strata of these two facies have grainstone filling the areas between individual thrombolites or stromatolites, and most of these strata probably are of shallow subtidal origin. Lithology 12, oncoid grainstone, is rare, it usually occurs immediately above sequence boundaries, and it is interpreted as a very shallow, probably peritidal, deposit.

We recognize four varieties of lithology 13, chert. Most common is brown to black chert that occurs as nodules, stringers, and thin beds, typically in subtidal lime mudstones. Burrowed mudstone commonly has brown to black chert replacing burrows. Laminated sandy or argillaceous carbonate may have brown chert replacing the sandy or argillaceous partings; this replacement is common in lithology 9. The most unusual variety of chert is bedded white to brown to black chert that may be laminated with cross-laminated sets, and such chert appears to have formed by diagenetic recrystallization of carbonate containing abundant quartz sand. This unusual chert commonly is associated with lithology 9 and is interpreted to have formed from strata deposited in peritidal to tidal-flat environments.

Lithology 14, dolomite, formed by secondary replacement of a variety of limestones. Much of the dolomite is coarsely crystalline, and original depositional fabrics typically are not preserved. However, Notch Peak dolomites often preserve original fabrics of stromatolites and thrombolites. Most of the dolomite we studied is confined to the Hellnmaria Member in the Lawson Cove and Steamboat Pass sections. An exception is the Drum Mountains section, where nearly all of the Notch Peak Formation and the lowest beds of the House Limestone are dolomite.

Lithology 15, zebra-rock dolomite, is quite unusual. It consists of irregular bands or laminae of white crystalline dolomite alternating with black to dark gray dolomite. The bands or laminae range from a few mm to as much as ten cm thick, although most bands are less than one cm thick. Isolated crystals of calcite up to 10 cm long occur near the middle of a few white dolomite bands. Zebra rock occurs near the lower part of the dolomitic portion of the Hellnmaria Member in the Lawson Cove and Steamboat Pass sections (Hintze et al., 1988, p. 25, units 7, 9; p. 27, units 3, 11), in the Drum Mountains section in the upper Hellnmaria Member (units 1, 2), and in the lower part of the House Limestone (unit 15). The banding is parallel to bedding in all of these strata. Zebra rock also occurs as laminae within stromatolites near the top of the Hellnmaria Member just below the base of the Lawson Cove measured section and in the Lava Dam Member at the Drum Mountains section (unit 9). These occurrences lead us to interpret zebra rock as a recrystallized microbial fabric. The more common deposits that are parallel to bedding probably represent a microbial mat that is peritidal to supratidal in origin. Zebra rock has never been found as limestone, only as dolomite.

Lithology 16, shale, is common in the Steamboat Pass Shale and Corset Springs Shale members of the Orr Formation, the lowermost strata considered herein. A thin band of shale occurs within the Barn Canyon Member at Lava Dam North. These occurrences are interpreted as having been deposited during sea-level lowstands and to be of shallow marine origin.

Lithology 17, quartz sandstone, is quite rare, is associated with sequence boundaries, and may be of non-marine origin. Lithology 18, evaporite minerals, occur at only two horizons and may be mixed with shale. These occurrences are interpreted to be at the low points of sea-level lowstands and to be peritidal to supratidal in origin. The one occurrence of lithology 19, chert-clast conglomerate, is a basal conglomerate above an unconformity and probably is of peritidal origin.

The Hellnmaria Member displays north-south variation in dolomite vs. limestone lithology. The lower part of the Hellnmaria, 440 ft (134.1 m) at Lawson Cove and 374 ft (114.0 m) at Steamboat Pass, consists of lime mudstone, and the depositional environment shallows upward to zebra-rock dolomite. The middle to upper part of the Hellnmaria, 900 ft (478.2 m) at Lawson Cove and 669 ft (203.9 m) at Steamboat Pass, is almost entirely dolomite and includes numerous stromatolitic or thrombolitic intervals. By contrast, Hellnmaria sections in the Sneakover Pass and Chalk Knolls areas are entirely limestone and comprise a shallowing-upward succession much like that in the southern House Range and northern Wah Wah Mountains. The lower to middle parts of the Hellnmaria at East Shoreline Butte are thin-bedded to laminated, dark lime mudstone that appears to represent rather deep subtidal conditions, whereas the upper part of the Hellnmaria contains ooid grainstone, stromatolitic boundstone, and oncoid grainstone that represent much shallower conditions. The Hellnmaria Member in the northern Drum Mountains and nearby areas to the east is nearly all dolomite with stromatolitic intervals in the upper part. Dommer (1980, p. 63) mapped the Notch Peak in the Drum Mountains and reported that all but its uppermost part is dolomite.

The Red Tops Member displays relatively little lithofacies variation across the same north-south traverse. It consists of shallow, high-energy brown to rusty grainstone and flat-pebble conglomerate over most of this area. A stromatolitic interval occurs at Lawson Cove, Steamboat Pass, Sevier Lake Corral, Notch Peak, and several such intervals occur in the Chalk Knolls area.

The lower part of the Lava Dam Member is consistently cherty lime mudstone in most sections but is dolomite in the Drum Mountains. The most pronounced lithofacies variation across the north-south traverse is in the middle to upper part of the Lava Dam Member. The Tank Canyon Bed, a thin marker bed of ooid grainstone, is present from Lawson Cove northward to the Notch Peak section. The Tank Canyon Bed, a thin stromatolite biostrome, is present from Lawson Cove northward to Sheakover Pass. These two beds are absent in the House Range Embayment farther north. Upper Lava Dam strata tend to be stromatolitic or thrombolitic boundstone with some cherty lime mudstone near Skull Rock Pass and at Lawson Cove, but this interval is almost ertirely cherty lime mudstone in the southern House Range. In the Drum Mountains these strata are dolomitic and partly stromatolitic. A coquina consisting mostly of the trilobite *Symphysurina* marks a change in depositional pattern at the Notch Peak-House contact.

The House Limestone has relatively few strata of microbial origin but consists mostly of thin to medium beds of limestone. Beds and nodules of white to brown to black chert occur in the lower part of the Barn Canyon Member but are absent at Chalk Knolls and Drum Mountains.

CONODONT BIOSTRATIGRAPHY

J. F. Miller and R. L. Ethington

INTRODUCTION

The conodont biozonation of the Notch Peak and House formations is among the best known in the world for the upper Cambrian-lower Ordovician interval. Collections from many sections are spaced at very close intervals and provide a high level of precision for subdivision of this thick interval of strata. Ross et al. (1997) summarized the conodont biostratigraphy of strata in the Ibex area. The biozonal framework utilized herein is nearly the same as in that report, with the exception that the *Cordylodus lindstromi* sensu lato Zone and the *Rossodus manitouensis* Zone are each divided into subzones in this report.

There are also differences in the taxonomic nomenclature utilized in this report compared with nomenclature utilized by Ross et al. (1997), which is based on previously published reports by Ethington and Clark (1981) and Hintze et al. (1988). These differences are partly because of changes introduced in subsequent reports and partly because of the discovery of new taxa based on new and larger collections. Because this report does not contain a section on systematics, new taxa are placed in open nomenclature and will be described in later reports.

Tables 2–7 (CD-ROM) provide documentation of the mass of dissolved conodont samples at East Shoreline Butte, Chalk Knolls North, Lawson Cove, Lava Dam North, and the 1965 C sections, although the masses of some samples are estimated and thus require explanation. In many cases samples contained so many conodonts that they were picked from only part of the heavy fraction of the insoluble residue. In such cases the picked proportion was estimated, and the amount of rock processed was adjusted on Tables 2–7 so as to give some basis for calculating the number of conodonts recovered per kilogram of rock. Sample masses adjusted in this way are indicated by the letter "e" (estimated) appearing after the sample mass. The complete sample mass for conodont samples from nine sections is recorded in Tables 9–19 (CD-ROM). The statistic "number of conodonts per kilogram" was calculated for general information.

Conodonts have different abundances in strata discussed herein, and there is a general increase in abundance in younger stratigraphic units. Faunas of the Hellnmaria Member are relatively low in abundance, and taxa of biostratigraphic utility do not appear until the middle of that member. Recovery of fossils is low to nonexistent in dolomite facies, although some faunas were recovered in the Drum Mountains section in dolomite facies of the Hellnmaria. Conodonts are more abundant in the Red Tops Member and in the lower (Millardan) part of the Lava Dam Member. The upper (Ibexian) part of the Lava Dam, the House Limestone, and the lower Fillmore Formation in the Ibex area have abundant conodonts.

Most of the conodonts reported herein are from the Lawson Cove and Lava Dam North sections. Of more than 200 samples collected for conodonts at Lawson Cove, the only unproductive ones were two dolomite samples (upper Hellnmaria and basal Red Tops) and two limestone samples from near the middle of the Lava Dam. Lawson Cove samples yielded 45,045 identified elements, and Lava

Dam North samples yielded 16,277 identified elements. Samples from East Shoreline Butte produced 2088 elements, and samples at Chalk Knolls North produced 1134 elements. These collections, which total 64,544 identified elements, form the basis for the conodont biozonation discussed below. Except for two dolomitic limestones near the top of the House Limestone at Lava Dam North, all samples from the House Limestone and lower Fillmore produced conodonts. Preservation of conodonts is generally good. The Color Alteration Index of conodonts from sections in the Ibex area is about 3–4 (gray), although some faunas may have CAI as high as 4.5 (dark gray).

The biozones utilized herein are Interval Zones, that is, the bases of zones are at the lowest occurrence of one or more diagnostic taxa, and the tops of zones are at the base of the overlying zone. Several of the zones also fit the definition of Range Zones because the base and top of the biozone coincide with the lowest and highest occurrences of the diagnostic taxon.

The biozonation is based on several evolving lineages of conodonts (Miller, 1980; Chen and Gong, 1986). Many of the zonal units are based on species of the *Proconodontus* lineage. This lineage consists of a succession of species of *Proconodontus* Miller, then *Eoconodontus* Miller, followed by *Cambrooistodus* Miller, and finally by *Cordylodus* Pander. Other biozonal units are based on evolutionary diversification among three other lineages. The *Dasytodus* lineage of Chen and Gong (1986) includes *Clavohamulus* Furnish and *Hirsutodontus* Miller; this lineage is especially useful for biozonation. The unusual conodont *Fryxellodontus* Miller constitutes a lineage unto itself. *Teridontus* Miller is the ancestor of a lineage that includes such coniform genera as *Acanthodus* Furnish, *Monocostodus* Miller, *Polycostatus* Ji and Barnes, *Rossodus* Repetski and Ethington, *Semiacontiodus* Miller, and *Utahconus* Miller. The diversification among these lineages shows the successful adaptation of early euconodonts to changing environments. Strata considered herein also contain representatives of paraconodont evolutionary lineages, but these are of little use for detailed biostratigraphy. An exception is *Albiconus* Miller, which occurs first at or near the base of the *Cordylodus intermedius* Zone and is useful for recognizing the base of that zone.

Conodonts recovered in the Ibex area are typical of faunas in coeval strata in Nevada, Texas, Oklahoma, Colorado, and various parts of the eastern United States. The succession of faunas is quite uniform in all of these areas, and the conodont succession in the Ibex area is essentially complete and without significant gaps so far as is known after decades of study of the strata and faunas. We can identify small hiatuses at sequence boundaries in some sections based on lithologic features, but the stratigraphic succession includes all conodont biostratigraphic units. The only exception is in the Drum Mountains section, which has no record of the *Hirsutodontus hirsutus* Subzone of the *Cordylodus proavus* Zone. The Ibexian faunal succession constitutes a good reference standard for correlation. Many of the taxa found in this area are widely distributed in other parts of the world (Canada, China, Kazakhstan, and Australia) and form the basis for global correlation of strata of this age.

Stratigraphic ranges of conodonts and other fossils are shown on Figures 4–12. The relationships to lithostratigraphic, sequence stratigraphic, and chronostratigraphic units of the biostratigraphic units shown on those range charts are shown on Figures 2–3. The numbers of specimens, masses of samples, and other data are provided in Tables 2–8.

The oldest conodonts are from limestone facies in the lower part of the Hellnmaria Member at East Shoreline Butte and Chalk Knolls North (Fig. 1, locations Q and O). These strata yielded a diverse fauna of protoconodonts and paraconodonts, although such faunas have not been shown to be useful for detailed biostratigraphy. The upper part of the Hellnmaria at those sections yielded primitive euconodonts faunas diagnostic of the *Proconodontus tenuiserratus* Zone and the *P. posterocostatus* Zone. Faunas diagnostic of the *Proconodontus posterocostatus* Zone also occur in a dolomite facies in the Drum Mountains (Fig. 1, location R) and in limestone facies at Sneakover Pass and Notch Peak. The youngest faunas discussed in this study are from the Low Diversity Interval in the lower part of the Fillmore Formation at the 1965 C section.

The biostratigraphy of all sections is well understood, although conodont faunas are most thoroughly documented at East Shoreline Butte, Chalk Knolls North, Lawson Cove, Lava Dam Five, Lava Dam North, and 1965 C. Stratigraphic intervals assigned to various conodont biostratigraphic units are summarized in Table 9 for all sections except Chalk Knolls, which was abandoned due to faulting.

Nearly all of the conodont biostratigraphic units discussed below are recognized in the Threadgill Creek or Lange Ranch sections in Texas. However, exposures there do not include strata as young as the Low Diversity Interval that is present in the lower Fillmore Formation in Utah.

PROCONODONTUS TENUISERRATUS ZONE

The oldest conodont zone defined in North America is the *Proconodontus tenuiserratus* Zone. Its base is at the lowest occurrence of *P. tenuiserratus* Miller; its top is at the base of the *P. posterocostatus* Zone. The zone is characterized by the presence of the primitive euconodont species used to name the zone. Various relatively long-ranging protoconodont and paraconodont species also occur in this zone, which is recognized in the middle part of the

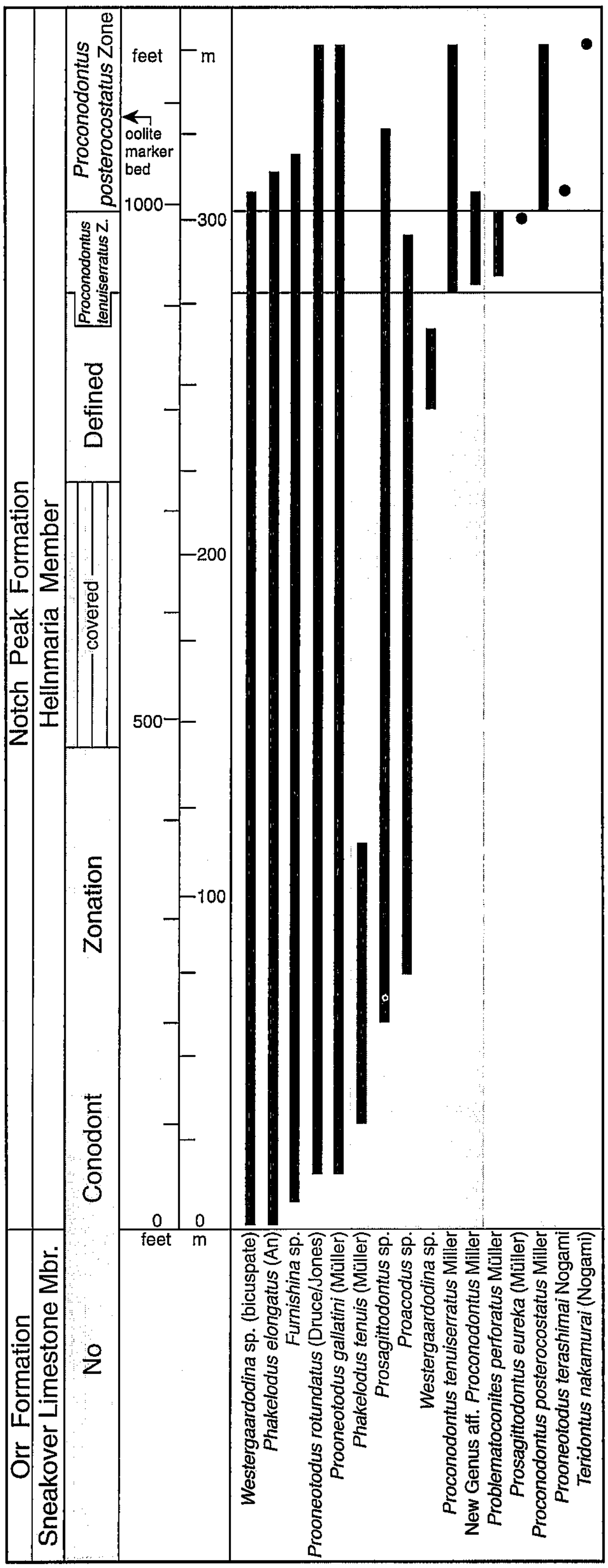


Figure 4. Ranges of conodont taxa and derived conodont biostratigraphic units in the East Shoreline Butte section. For detailed occurrence data, see Table 2 on CD-ROM.

Hellnmaria Member in the East Shoreline Butte and Chalk Knolls North sections (Figs. 4, 5; Tables 2, 3, 8).

PROCONODONTUS POSTEROCOSTATUS ZONE

The base of the *Proconodontus posterocostatus* Zone is at the lowest occurrence of *P. posterocostatus* Miller; its top is at the base of the *P. muelleri* Zone. *P. posterocostatus* is the only characteristic species that is confined to the zone. *Proconodontus tenuiserratus* may extend into the zone from below, and various long-ranging protoconodont and paraconodont species also occur in the zone. Occasional specimens of the euconodont *Teridontus* sp. may occur near the top of the zone. This zone is recognized in the upper (but not uppermost) part of the Hellnmaria Member at the Notch Peak, East Shoreline Butte, Chalk Knolls North, and Drum Mountains sections (Figs. 4, 5; Tables 2, 3, 8). One sample representing this zone was recovered from near the base of the described portion of the Sneakover Pass section. The characteristic fauna of this zone also occurs in samples from the Hellnmaria Member at Coyote Knolls, in the northern part of Tule Valley. J. F. Miller processed these samples for Lehi Hintze, who collected them from a reconnaissance section (Hintze, pers. comm.).

PROCONODONTUS MUELLERI ZONE

The base of the *Proconodontus muelleri* Zone is at the lowest occurrence of *P. muelleri* Miller; its top is at the base of the *Eoconodontus* Zone. Besides *P. muelleri*, specimens of the euconodont *Teridontus* sp. and various long-ranging protoconodonts and paraconodonts may occur in the zone. *Proconodontus muelleri* is often the only euconodont species occurring in this zone. Samples from this zone and the underlying *P. tenuiserratus* and *P. posterocostatus* zones typically do not have more than one species of euconodont, unless the ranges of two species of this genus overlap in the lower part of one of the zones.

The *Proconodontus muelleri* Zone comprises the uppermost part of the Hellnmaria Member and the lower part of the Red Tops Member (Fig. 6, Tables 4, 8). The zone is developed best at Steamboat Pass in a sequence of gray lime mudstone at the top of the Hellnmaria; lime grainstone at the base of the Red Tops Member is also assigned to this zone. Conodonts from this section were reported by Hintze et al. (1988). The lime mudstones at the base of the Red Tops are not present at Lawson Cove, but coeval strata are the dolomite facies of the upper Hellnmaria and basal Red Tops. The oldest conodonts recovered at Lawson Cove are two small collections containing only *P. muelleri* from the top 5 ft (1.5 m) of the Hellnmaria; these dolomites and an ooid dolomite at the base of the Red Tops are assigned to this zone. The *P. muelleri* Zone is also well

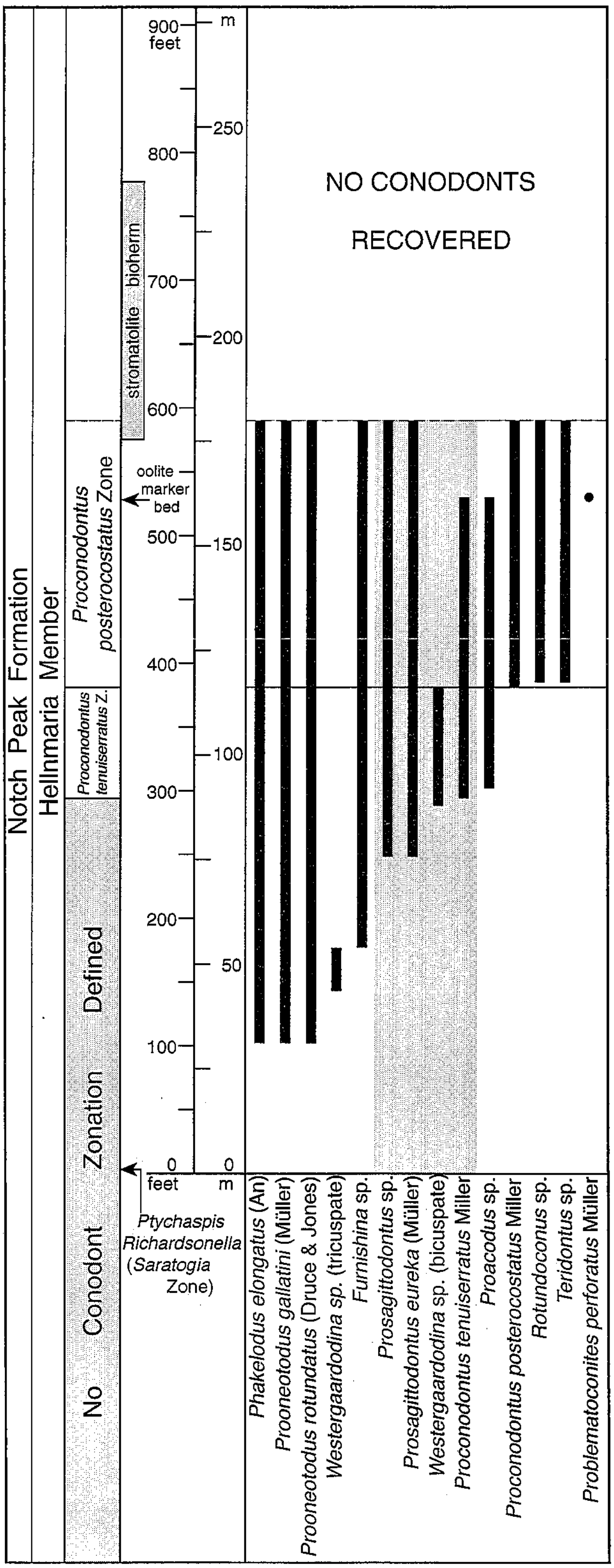


Figure 5. Ranges of conodont taxa and derived conodont biostratigraphic units in the Chalk Knolls North section. For detailed occurrence data, see Table 3 on CD-ROM.

documented in the uppermost strata of the Hellnmaria and lower Red Tops at Sneakover Pass and Notch Peak. The zone has sparse faunas at Chalk Knolls South, Chalk Knolls Middle, and Drum Mountains.

EOCONODONTUS ZONE

The *Eoconodontus* Zone is the highest conodont zone of the Millardan Series, and it directly underlies strata assigned to the Ibexian Series. The base of the zone is at the lowest occurrence of *E. notchpeakensis* (Miller). The top of the zone is at the base of the overlying *Cordylodus proavus* Zone, at the lowest occurrence of *Cordylodus andresi* Sergeeva and Viira. An evolutionary succession of taxa descended from *Proconodontus muelleri,* including *P. serratus* Miller, *Eoconodontus notchpeakensis,* and species of *Cambrooistodus* Miller characterize faunas of this zone. The top of the zone is at a major extinction and faunal turnover. The zone is divided into the *E. notchpeakensis* Subzone and the overlying *Cambrooistodus minutus* Subzone. Both subzones are widely distributed in the Ibex area and occur in the Red Tops and lower Lava Dam members (Fig. 6, Tables 4, 8). Conodonts from this zone at Steamboat Pass and Lava Dam Five were tabulated by Hintze et al. (1988).

The *Eoconodontus* Zone has not been subdivided at the Lava Dam South, Sevier Lake, and Notch Peak sections (Table 9). Ranges of critical taxa are not well established in those sections, and so only the overall zone is recognized. The presence of the zone is well established at Chalk Knolls Middle, but the zone is deceptively thick due to faults that duplicate strata, probably several times.

Eoconodontus notchpeakensis Subzone

The lower subzone of the *Eoconodontus* Zone is the *Eoconodontus notchpeakensis* Subzone. The base of the subzone is at the lowest occurrence of *Eoconodontus notchpeakensis,* and its top is at the base of the *Cambrooistodus minutus* Subzone. The top of the subzone is at the highest exposed bed of the Red Tops Member at Lawson Cove, sample LCL-RT36; younger Red Tops strata are covered at this locality. The subzone typically occurs in the middle part of the Red Tops Member (Table 9). Several conodont species typically occur in this subzone, including the euconodonts *Cambrooistodus cambricus* (Miller), *Proconodontus muelleri,* and *P. serratus,* as well as unrelated genera of paraconodont and protoconodont lineages such as *Furnishina* Müller, *Phakelodus* Miller, *Prooneotodus* Müller, *Prosagittodontus* Müller, and *Westergaardodina* Müller (Fig. 6). Any of these taxa may also occur in the overlying subzone, and some are found at much higher horizons. None of these paraconodonts is useful for detailed biostratigraphy. Their distribution is not discussed

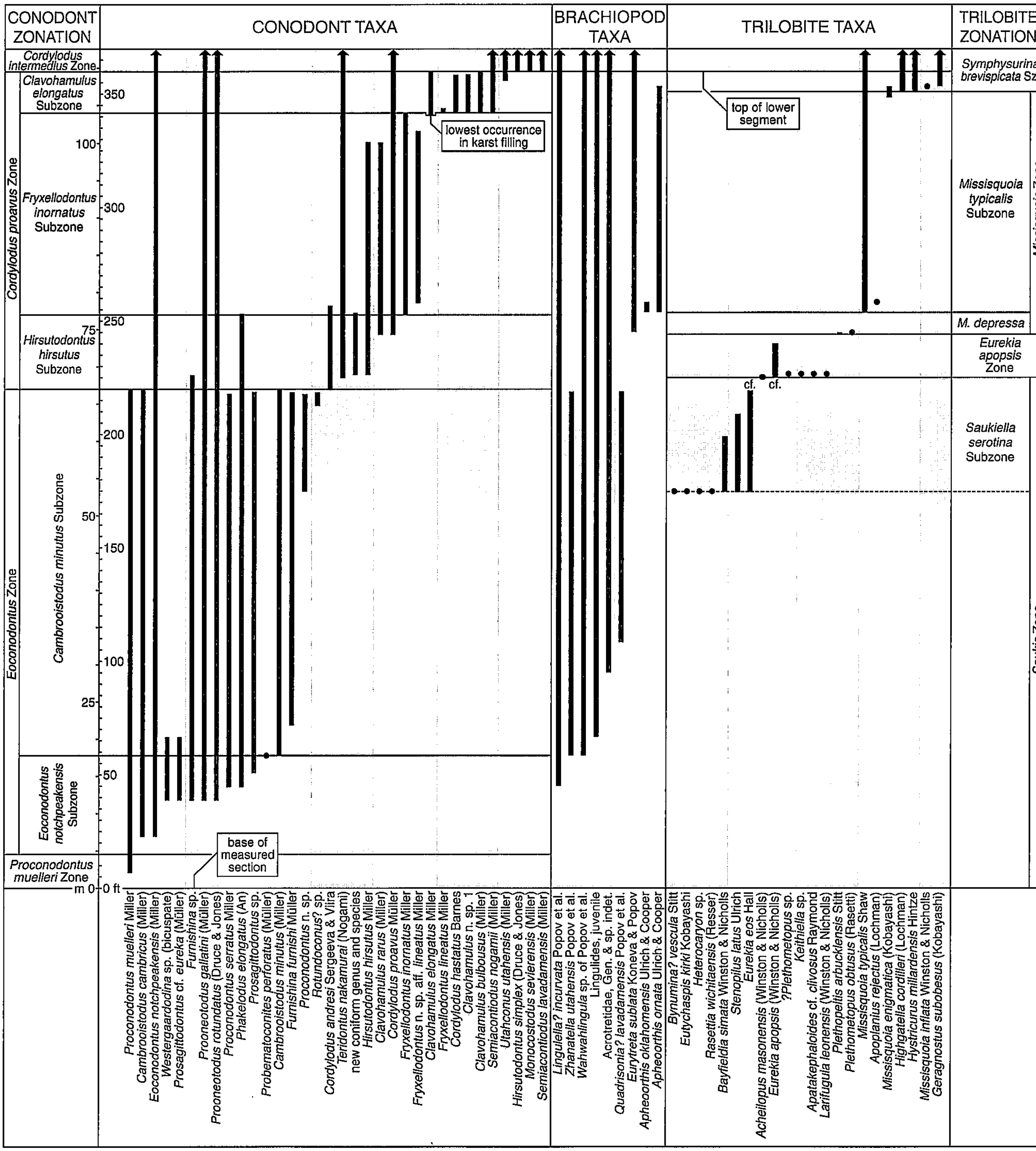


Figure 6. Ranges of conodont, brachiopod, and trilobite taxa and derived conodont and trilobite biostratigraphic units in the lower segment of the Lawson Cove section. For detailed occurrence data, see Table 4 on CD-ROM.

subsequently, but their occurrences are recorded on the range charts and in the data tables. The phosphatic microfossil *Palaeobotryllus taylori* Müller, purported to be a fossil tunicate, often occurs in this subzone, sometimes in large numbers.

Cambrooistodus minutus Subzone

The upper subzone of the *Eoconodontus* Zone is the *Cambrooistodus minutus* Subzone. The base of the subzone is at the lowest occurrence of *C. minutus* (Miller), and the top is at the base of the *Cordylodus proavus* Zone, at the lowest occurrence of *Cordylodus andresi*. The *Cambrooistodus minutus* Subzone encompasses the highest part of the Red Tops Member and ca. the lowest half of the Lava Dam Member (Table 9). The top of the subzone is at sample LCL-LD158, which contains both the highest occurrences of *Cambrooistodus cambricus, C. minutus,* and *Proconodontus muelleri* and also the lowest occurrence of *Cordylodus andresi* (Table 6, Fig. 6). All euconodont species that occur in the underlying *Eoconodontus notchpeakensis* Subzone may be found in the *Cambrooistodus minutus* Subzone as well.

Near the top of the subzone, samples LCL-LD151, 156, and 157 contain an unusual erect coniform element with fine granulose ornament. This is *Rotundoconus*? sp., a species that occurs at this level at the nearby Lava Dam Five section and at the top of this subzone in the Lange Ranch section in Texas. Also occurring rarely, usually in just the upper part of this subzone, is a new species of *Proconodontus* illustrated by Miller (1969, Pl. 63, Figs. 51–53). *Palaeobotryllus taylori* may occur in the lower part of this subzone; it appears to be characteristic of the Red Tops Member.

Strata assigned to the *Proconodontus tenuiserratus* Zone through the *Eoconodontus* Zone comprise the upper part of the Sunwaptan Stage, the uppermost stage of the Millardan Series. Overlying strata of the Notch Peak and House formations are assigned to the Ibexian Series and to its Skullrockian Stage. The boundary between the Millardan Series and the Ibexian Series is at a major extinction event among conodonts. Euconodont species occurring in upper Millardan strata are *Cambrooistodus cambricus, C. minutus, Eoconodontus notchpeakensis, Proconodontus muelleri, P. serratus,* and *P.* n. sp., all part of the *Proconodontus* lineage. At Lawson Cove all of these species except the rare species *Proconodontus serratus* are present near the top of the *C. minutus* Subzone in samples LCL-LD156 and 157 (Fig. 4). Only 2 ft (0.6 m) higher, all of these species have disappeared, although *E. notchpeakensis* is found in younger strata. A major extinction among trilobites is documented at the same level. This extinction event is a major punctuation mark in Earth history and separates the Millardan Series from the Ibexian Series. Ross et al. (1997, Fig. 8) documented a similar faunal turnover at this level at Lava Dam Five, and comparable relationships are found at other sections in the Ibex area. Lithologic evidence indicates a relative drop in sea level at this horizon in several sections, but an unconformity is present only in the Drum Mountains section.

CORDYLODUS PROAVUS ZONE

The *Cordylodus proavus* Zone is the lowest zone of the Ibexian Series and of its Skullrockian Stage. The base of the zone is at the lowest occurrence of *Cordylodus andresi*; at Lawson Cove the lowest occurrence of *Cordylodus proavus* is 24 ft (7.3 m) above the base of the zone (Fig. 6). The top of the zone is at the base of the overlying *Cordylodus intermedius* Zone, at the lowest occurrence of *Hirsutodontus simplex* (Druce and Jones). The *C. proavus* Zone occurs in the upper half of the Lava Dam Member, and the top of the zone is close to the Notch Peak-House contact (Fig. 1). Distribution of the zone is documented in Table 9. The complete zone is present in the lower segment of the composite Lawson Cove section. Occurrences of conodonts from this zone at Steamboat Pass and Lava Dam Five were tabulated by Hintze et al. (1988). The *C. proavus* Zone is divided into the *Hirsutodontus hirsutus, Fryxellodontus inornatus,* and *Clavohamulus elongatus* subzones.

Hirsutodontus hirsutus Subzone

The lowest and thinnest division of the *Cordylodus proavus* Zone is the *Hirsutodontus hirsutus* Subzone. The base of this subzone is at the lowest occurrence of *Cordylodus andresi*. At Lawson Cove, the sample with the lowest occurrence of *C. andresi* also contains the highest occurrences of taxa characteristic of the underlying *Cambrooistodus minutus* Subzone. This relationship is displayed also at the Lava Dam Five section, where the base of the Ibexian Series was placed at a sample with a similar co-occurrence of these taxa. The top of the *H. hirsutus* Subzone is at the base of the overlying *Fryxellodontus inornatus* Subzone. The *H. hirsutus* Subzone occurs near the middle of the Lava Dam Member (Table 9).

Conodonts in the lower part of this subzone are an order of magnitude less abundant at Lawson Cove than in directly underlying samples, and the next two higher samples are the only barren limestone samples in the Lawson Cove section (Table 4). The next few younger samples have very few conodont elements, but the number of elements per sample slowly increases upward. It is clear that the lowest part of this subzone is an interval of mass extinction and faunal turnover, followed by slow recovery of a mostly new and less diverse fauna. Not until the upper part of the subzone do numbers of conodont elements exceed 100 per kg of rock dissolved (Table 4).

Several conodonts besides *Cordylodus andresi* are characteristic of this subzone. *Teridontus nakamurai* (Nogami) and *Hirsutodontus hirsutus* Miller are introduced within the lower part of the subzone, and the lowest occurrences of *Cordylodus proavus* Müller and *Clavohamulus rarus* (Miller) are in the upper part of the subzone (Fig. 6). The lowest occurrence of *Cordylodus proavus* in sample LCL-LD182 coincides with a sharp rise in abundance of conodont elements (Table 4). That sample was collected at the base of the *Missisquoia* Trilobite Zone, at the lowest occurrence of *Plethopeltis arbucklensis* Stitt. The lowest occurrence of the organophosphatic brachiopod *Eurytreta* Rowell is only 1 ft (0.3 m) higher. This sample marks the start of an evolutionary succession through several species of this genus that occur higher in the section. The thin interval represented by samples LCL-LD182 to 183 is marked by virtually coincident appearances of new taxa among conodonts, trilobites, and brachiopods (Fig. 6). This level is the base of the traditional Canadian Series as recognized by Stitt (1977) and show on Figure 3 herein.

Two informal parts of the *Hirsutodontus hirsutus* Subzone can be recognized, although there is no available terminology by which to recognize divisions of a subzone. The lower part of the subzone is characterized by the presence of *Cordylodus andresi*, the most primitive species of the genus, and by the absence of its descendant species, *C. proavus*. The upper part of the *H. hirsutus* Subzone is characterized by the presence of both species. Some authors have recognized a thin *Cordylodus andresi* Zone that correlates with the informal lower part of this subzone. The base of the *Cordylodus proavus* Zone recognized by those authors correlates with the lowest occurrence of *C. proavus* recognized in this report within the *H. hirsutus* Subzone, at sample LCL-LD-182. The lowest occurrence of each of these species also coincides with important sequence stratigraphic boundaries.

Fryxellodontus inornatus Subzone

The middle subzone of the *Cordylodus proavus* Zone is the *Fryxellodontus inornatus* Subzone. The base of the subzone is at the lowest occurrence of *F. inornatus* Miller. The top of the subzone is at the base of the overlying *Clavohamulus elongatus* Subzone. The entire subzone is present in the lower segment of the Lawson Cove section. The lower part of this subzone is characterized by very abundant conodont elements (Table 4), but the abundance is reduced sharply at the bottom of a thick stromatolite mound, in sample LCL-LD229. This mound is not present in equivalent strata in the middle segment of the section. However, these nearby strata must have been deposited on the flanks of this mound, and conodont abundances are similarly low when compared with recoveries from strata in the stromatolitic mound (Table 5). The *F. inornatus* Subzone usually occurs in the upper part of the Lava Dam Member but below its top (Table 9).

A subtle but important conodont faunal change occurs in the lower part of this subzone. Samples LCL-LD191 to 196 are characterized by several species that occur in the underlying *Hirsutodontus hirsutus* Subzone, including *H. hirsutus* and *Cordylodus andresi*. The latter occurs in samples LCL-LD191 to 195 but does not occur higher in the section; the top of its range appears to characterize the lowest part of the *F. inornatus* Subzone. Single elements of *H. hirsutus* occur in samples LCL-LD195 and 196, and the species occurs only rarely in younger strata (Tables 4, 5). One new faunal element appears just above the disappearance of *C. andresi*, namely *Fryxellodontus* n. sp. aff. *lineatus* Miller. This species characterizes the portion of the *F. inornatus* Subzone above the range of *C. andresi*. This slight change in fauna coincides with the top of the Lawson Cove Bed, at sample LCL-LD195.

This subtle faunal change above the Lawson Cove Bed makes it possible to divide the *Fryxellodontus inornatus* Subzone into two informal parts, similar to the two informal parts of the underlying *Hirsutodontus hirsutus* Subzone. The lower part is characterized by the presence of *F. inornatus* and *Cordylodus andresi* and by the absence of *F.* n. sp. aff. *lineatus*. This lower part of the subzone is only 5 ft (1.5 m) thick (samples LCL-LD191 to 196), and it coincides with the lower part of the *Missisquoia typicalis* Trilobite Subzone (Fig. 6). The upper part is characterized by the absence of *Cordylodus andresi* and by the presence of *Fryxellodontus inornatus* and *F.* n. sp. aff. *lineatus*. The new species of *Fryxellodontus* was illustrated by Miller (1969, Pl. 65, Fig. 11 only) and is characterized by vertical linear ornament, whereas the younger species *F. lineatus* Miller is characterized by horizontal linear ornament. The upper part of the subzone is characterized also by the presence of the trilobite *Apoplanius rejectus* (Lochman), which does not occur in the lowest part of the *Missisquoia typicalis* Subzone (Fig. 6).

The ability to recognize two parts in each of the lower two subzones of the *Cordylodus proavus* Zone reflects the rapid evolutionary diversification of the new conodont faunas that appeared after the major extinction at the base of the Ibexian Series. This diversification is also reflected in rapid changes in trilobite and brachiopod faunas through the same interval (Fig. 6). These rapid faunal changes are also related to rapid sea-level changes that are discussed in the section of this report dealing with sequence stratigraphy.

Clavohamulus elongatus Subzone

The upper subzone of the *Cordylodus proavus* Zone is the *Clavohamulus elongatus* Subzone. An abundant and diverse conodont fauna characterizes strata assigned to this subzone. The base of the subzone at Lawson Cove is at the lowest occurrence of *Clavohamulus elongatus* Miller, *C. bulbousus* (Miller), *C.* n. sp. 1, *Cordylodus hastatus* Barnes, *Fryxellodontus lineatus,* and *Semiacontiodus nogamii* (Miller). The entire subzone is represented in both the lower and the middle segments of the composite Lawson Cove section. The top of the subzone is at the base of the *Cordylodus intermedius* Zone, at the lowest occurrence of *Hirsutodontus simplex.* In both segments this horizon also coincides with the highest occurrence of *Clavohamulus elongatus.* Other characteristic species of the subzone, including *Clavohamulus bulbousus, Clavohamulus* n. sp. 1, *Cordylodus hastatus,* and *Fryxellodontus lineatus,* extend to the top of the subzone or to only 1 ft (0.3 m) below the top (Tables 4, 5). The *C. elongatus* Subzone occurs at the top of the Lava Dam Member and rarely extends into the basal beds of the Barn Canyon Member.

The base of the subzone in the lower segment is noteworthy for its position relative to a major lithofacies shift. Strata comprising most of the underlying *F. inornatus* Subzone are massive, unbedded microbial boundstone with a sparse conodont fauna. Above the microbial unit is a sharp truncation surface at the base of a unit of bedded lime mudstone; this surface appears to be an unconformity. Detailed sampling across this surface reveals that the lowest occurrence of *C. elongatus* is at the top of the stromatolitic unit, immediately below this truncation surface. There is a lithologic change at the equivalent level in the middle segment of the section, but underlying strata are not microbial (Fig. 7).

We interpret that the occurrence of conodonts diagnostic of the *Clavohamulus elongatus* Subzone from just below the truncation surface, in sample LCL-LD277, is from material that filled small irregularities or microkarst cavities in the top of the microbial strata (Fig. 6). These conodonts could have been deposited during the start of deposition of lime mudstone strata above the truncation surface. Based on this interpretation, we place the base of the *Clavohamulus elongatus* Subzone at the base of the lime mudstone sequence, at sample LCL-LD278, and we interpret the occurrence of *C. elongatus* in sample LCL-LD277 as a stratigraphic leak. These two samples are from adjacent beds that are separated only by the truncation surface.

Near the top of this subzone in the middle segment are the lowest occurrences of *Monocostodus sevierensis* (Miller) and *Utahconus utahensis* (Miller), which generally characterize the overlying *Cordylodus intermedius* Zone (Fig. 7, Table 5). These two species occur with the highest occurrences of *Clavohamulus bulbousus, C. elongatus,* and other species that disappear at the top of the subzone. This overlap of the ranges of these species also occurs in the lower segment at Lawson Cove and at Lava Dam Five. The overlap of the faunas of the two zones demonstrates conclusively that there is continuity between the two faunas, despite the faunal turnover in this interval. This continuity is important because a significant lithofacies shift occurs immediately above the samples that mark the boundary between the *Cordylodus proavus* and *C. intermedius* zones. This lithofacies shift is used as the Notch Peak-House contact, and it is also an important sequence boundary.

There is a significant turnover of the fauna near the top of the *Clavohamulus elongatus* Subzone. *Fryxellodontus* is found nearly at the top of this subzone at Lawson Cove, in the sample below the lowest occurrence of *Monocostodus sevierensis.* The top of the subzone is characterized by the disappearance of three species of *Clavohamulus* and of *Cordylodus hastatus* and by the appearance of *Hirsutodontus simplex* (Druce and Jones). *Monocostodus* and *Utahconus* appeared just below the top of the *C. elongatus* Subzone, but in sections where the top of this subzone was not sampled as closely as at Lawson Cove, these two genera occur for the first time together with *H. simplex.* Slightly higher is the lowest occurrence of *Cordylodus intermedius* Furnish. The largest extinction and faunal turnover above the top of the *Eoconodontus* Zone (compare Figs. 6 and 7) characterize the top of the *Cordylodus proavus* Zone.

CORDYLODUS INTERMEDIUS ZONE

The *Cordylodus intermedius* Zone is the second conodont zone of the Skullrockian Stage. The base of the zone is at the lowest occurrence of *Hirsutodontus simplex.* At Lawson Cove the lowest occurrence of *Cordylodus intermedius* Furnish is 4 ft (1.2 m) above the base of the zone. The top of the zone is at the base of the overlying *Cordylodus lindstromi* sensu lato Zone, at the lowest occurrence of *C. prolindstromi* Nicoll at Lawson Cove or at the lowest occurrence of *C. lindstromi* Druce and Jones sensu lato in other sections. The complete zone is present in the middle segment of the composite Lawson Cove section. In most sections the base of the zone is less than 1 ft (0.3 m) below the Notch Peak-House contact as recognized by Miller et al. (2001), although most of this zone is in the Barn Canyon Member of the House Limestone. Hintze et al. (1988, p. 26–27) placed this formation contact 132 ft (40 m) higher at Lawson Cove, at a horizon that is now known to be the top of this zone. Occurrences of conodonts from this zone at Lava Dam Five are shown in the report of Hintze et al. (1988, Table 2). The *Cordylodus intermedius* Zone is divided into a lower *Hirsutodontus simplex* Subzone and an upper *Clavohamulus hintzei* Subzone.

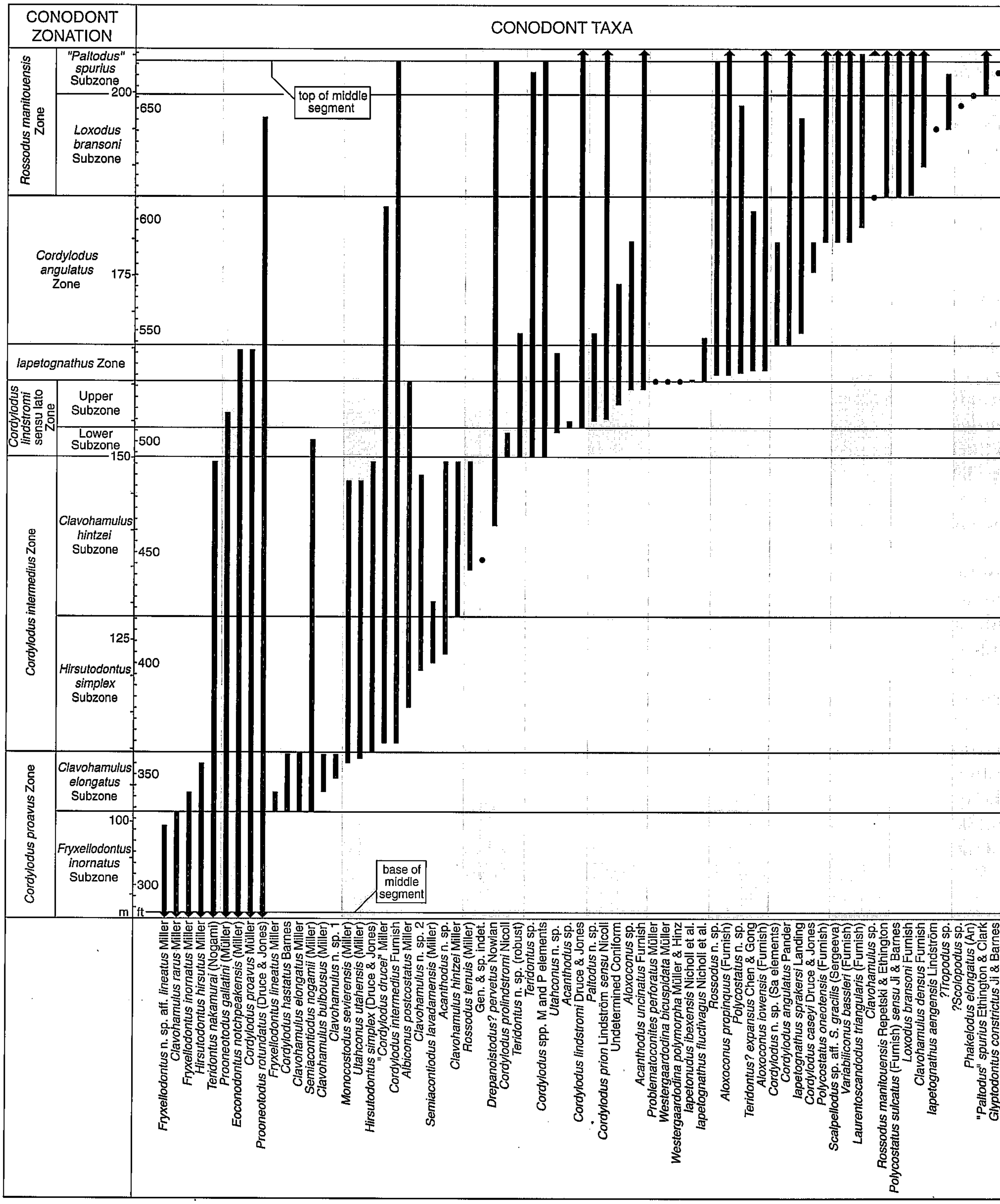


Figure 7. Ranges of conodont taxa and derived biostratigraphic units in the middle segment of the Lawson Cove section. Ranges of trilobites and brachiopods from the middle segment are shown on Figure 8. For detailed occurrence data, see Table 5 on CD-ROM.

Hirsutodontus simplex Subzone

The lower subzone of the *Cordylodus intermedius* Zone is the *Hirsutodontus simplex* Subzone. The base of the subzone is at the lowest occurrence of *H. simplex,* which coincides with the highest occurrences of *Clavohamulus elongatus* and several other taxa that are characteristic of the underlying subzone (Figs. 6, 7). The top of the subzone is at the base of the overlying *Clavohamulus hintzei* Subzone.

The fauna of the *Hirsutodontus simplex* Subzone is rather diverse. *Monocostodus sevierensis* and *Utahconus utahensis* are common in the *H. simplex* Subzone, but they originated near the top of the underlying subzone. Several other species are characteristic of this subzone, including *Albiconus postcostatus* Miller (a paraconodont), *Cordylodus "drucei"* Miller (a senior synonym of *C. caboti* Bagnoli, Barnes, and Stevens; *C. "drucei"* is interpreted herein to be one element of the apparatus of *Cordylodus intermedius* Furnish), *C. intermedius,* and *Semiacontiodus lavadamensis* (Miller) (Fig. 7). Several taxa in the upper part of the *H. simplex* Subzone appear to be ancestors of well known younger taxa. For example, near the top of the subzone and extending into the base of the overlying *Clavohamulus hintzei* Subzone are rare occurrences of *Clavohamulus* n. sp. 2, which was illustrated by Miller (1969; Pl. 64, Figs. 5 and 6 only), who originally referred the figured element to *Oneotodus* (now *Clavohamulus*) *bulbousus. Clavohamulus* n. sp. 2 is a generalized species of the genus and is never abundant, but it occurs in the upper part of the *H. simplex* Subzone in several lower House Limestone sections in the Ibex area (Fig. 7). It appears to be a precursor of the younger species *C. hintzei.* A new species of *Acanthodus* Furnish also occurs in the upper part of this subzone and may have evolved from *Monocostodus sevierensis.* Most taxa occurring in the *Hirsutodontus simplex* Subzone continue into the overlying *Clavohamulus hintzei* Subzone.

Clavohamulus hintzei Subzone

The upper subzone of the *Cordylodus intermedius* Zone is the *Clavohamulus hintzei* Subzone. The base of the subzone is at the lowest occurrence of *C. hintzei* Miller (Fig. 7). The top of the subzone at Lawson Cove is at the base of the overlying *Cordylodus lindstromi* s. l. Zone, at the lowest occurrence of C. *prolindstromi.* In other sections the base of the *Cordylodus lindstromi* s. l. Zone is at the lowest occurrence of *C. lindstromi* sensu lato. The *Clavohamulus hintzei* Subzone occurs in the lower to middle part of the Barn Canyon Member.

Conodonts are moderately abundant and diverse in this subzone (Table 5). Common species found only in this subzone are *Clavohamulus hintzei* and *Rossodus tenuis* (Miller). Several species that are typical of the *Cordylodus intermedius* Zone disappear at the top of the zone, including *Acanthodus* n. sp., *Clavohamulus hintzei, Hirsutodontus simplex, Monocostodus sevierensis, Rossodus tenuis, Semiacontiodus lavadamensis,* and *Utahconus utahensis.* Similar extinctions occurred at or near the tops of the *Eoconodontus* Zone and the *Cordylodus proavus* Zone, and all three of these extinctions coincide with important sequence boundaries (Figs. 6, 7).

Figure 7 and Table 5 show that *Teridontus nakamurai* (Nogami) also does not occur above this subzone, but this situation is more apparent than real. A new species of *Teridontus* occurs at the base of the next zone, and adult elements are more robust than elements identified as *T. nakamurai.* It is problematic whether smaller elements that occur together with this robust species are juveniles of the robust species or adults of the smaller species, *T. nakamurai.* The morphology of this genus is so simple that there are few characters to use in discrimination of species. Accordingly, these smaller elements of *Teridontus* are simply referred to as *Teridontus* sp. in strata above the base of the *Cordylodus prolindstromi* Zone.

The global distribution of *Clavohamulus hintzei* was documented recently by Lehnert et al. (1997). In addition to many occurrences in North America, the species occurs in Australia and in the Precordilleran displaced terrane in Argentina.

CORDYLODUS LINDSTROMI SENSU LATO ZONE

The *Cordylodus lindstromi* sensu lato Zone is the third conodont zone of the Skullrockian Stage. The base of the zone is placed at the lowest occurrence of *Cordylodus lindstromi* sensu lato or the lowest occurrence of *Cordylodus prolindstromi*; at Lawson Cove this horizon is in sample LCM-HL-401 and is at the lowest occurrence of *C. prolindstromi* (Table 5, Fig. 7). The top of the zone is at the base of the overlying *Iapetognathus* Zone, at the lowest occurrence of *Iapetognathus fluctivagus* Nicoll, Miller, Nowlan, Repetski, and Ethington. The zone is in the Barn Canyon Member of the House Limestone.

The *Cordylodus lindstromi* sensu lato Zone is divided into lower and upper subzones, but only at Lawson Cove. Subdivision of this zone is somewhat problematic because of a taxonomic problem. Druce and Jones (1971) named *Cordylodus lindstromi* from Australia, and the species was characterized by an extension of a secondary tip of the basal cavity into the first denticle. From a slightly lower level in the same Australian strata, Nicoll (1991) named *Cordylodus prolindstromi,* which he interpreted to be the ancestor of *C. lindstromi.* Nicoll considered that his species had a slightly different apparatus, and the secondary tip of the basal cavity had a slightly different shape. Each species was used to characterize a zone bearing the name of the species, and the ranges of the two species were said not to overlap.

Differentiating these two species has been controversial. Herein we accept that both species are valid, but morphologic differences between elements of the two species are slight. The symmetrical (Sa) elements of the symmetry transition series can be distinguished, but the Sa element is the rarest element of the apparatus, and it may not occur in small collections. If the two species can not be distinguished from each other because collections are small, it is useful to identify the material as *Cordylodus lindstromi* sensu lato.

The necessity of having two alternate taxonomic treatments (*Cordylodus prolindstromi* and *C. lindstromi* sensu stricto in one case versus *C. lindstromi* sensu lato in the other case) results in having two biostratigraphic treatments. Ross et al. (1997) considered the two species to be one species, *Cordylodus lindstromi* sensu lato. That species was used to characterize a single, rather thin *C. lindstromi* sensu lato Zone, which we recognize herein. If conodont collections from this interval are large and well preserved, it may be possible to differentiate a lower part of this zone that is characterized by *Cordylodus prolindstromi* and an upper part that is characterized by *Cordylodus lindstromi* sensu stricto. For this reason the overall zone is divided into a Lower Subzone that correlates with the *Cordylodus prolindstromi* Zone of Australia and an Upper Subzone that correlates with the lower part of the *Cordylodus lindstromi* sensu stricto Zone of Australia. However, the upper part of the latter zone presumably includes strata equivalent to the *Iapetognathus* Zone of this report. If *Cordylodus lindstromi* and *C. prolindstromi* can not be differentiated in a particular section, the entire interval of strata can be referred to the *Cordylodus lindstromi* sensu lato Zone.

At Lawson Cove, some *Cordylodus* elements from strata directly above the *C. intermedius* Zone are referred to *C. prolindstromi.* The lowest occurrence of the distinctive Sa element of *C. lindstromi* is somewhat higher, and it is found in many younger samples through most of the House Limestone. The two subzones are differentiated from each other only at Lawson Cove because conodont collections are not large enough in other sections to be able to discriminate the two species. Accordingly, one undifferentiated biostratigraphic unit, the *C. lindstromi* sensu lato Zone, is recognized in other sections.

Lower Subzone (New)

The base of the Lower Subzone of the *Cordylodus lindstromi* sensu lato Zone is at the lowest occurrence of *C. prolindstromi,* which at Lawson Cove is in sample LCM-HL401 (Table 5). The top of the subzone is at the base of the Upper Subzone. *Cordylodus prolindstromi* as recognized herein occurs only in samples LCM-HL401 through LCM-HL412. The Lower Subzone extends from LCM-HL412 to the base of the Upper Subzone, which is at the lowest occurrence of *C. lindstromi* sensu stricto, in sample LCM-HL414. The Lower Subzone is thus only 13 ft (4.0 m) thick (Fig. 5), it is not well exposed, and much of the upper half is covered in the only section where it is recognized.

Cordylodus prolindstromi and a robust new species of *Teridontus* are the only species having their lowest occurrences in this subzone, and both occur at its base (Fig. 7, Table 5). Only *Cordylodus prolindstromi* is confined to the *C. prolindstromi* Zone.

Upper Subzone (New)

The base of the Upper Subzone of the *Cordylodus lindstromi* s. l. Zone is at the lowest occurrence of *C. lindstromi* sensu stricto, in sample LCM-HL414 (Table 5). The top of the zone is at the base of the overlying *Iapetognathus* Zone, at the lowest occurrence of *Iapetognathus fluctivagus,* and the subzone is only 21 ft (6.4 m) thick at Lawson Cove. Conodonts are abundant in this subzone, but no species is confined to it. Besides *C. lindstromi* sensu stricto, several species have lowest occurrences within this subzone, including *Acanthodus uncinatus* Furnish, *Aloxoconus* sp., *Cordylodus prion* Lindström sensu Nicoll, *Paltodus* n. sp., *Utahconus* n. sp., and an undetermined coniform element that occurs in overlying strata as well (Fig. 7). The occurrences of these additional taxa produce a distinctive contrast with the Lower Subzone. *Cordylodus prion* and *Utahconus* n. sp. are especially useful in characterizing the Upper Subzone because they occur at its base, although the former species is quite rare.

IAPETOGNATHUS ZONE

The *Iapetognathus* Zone is the fourth conodont zone of the Skullrockian Stage. The base of the *Iapetognathus* Zone is at the lowest occurrences of *Iapetognathus fluctivagus* and *Iapetonudus ibexensis* Nicoll, Miller, Nowlan, Repetski, and Ethington. The top of the zone is at the base of the *Cordylodus angulatus* Zone. This zone is 16.5 ft (5.0 m) thick at Lawson Cove and occurs in the middle part of the Barn Canyon Member. Both taxa that characterize the base of this zone were described recently by Nicoll et al. (1999). *Iapetonudus ibexensis* is considered to be the ancestor of *Iapetognathus fluctivagus,* which is interpreted to be the oldest of several species of this unusual ramiform genus.

Several new coniform taxa have lowest occurrences in this zone, including *Aloxoconus iowensis* (Furnish), *A. propinquus* (Furnish), *Teridontus? expansus* Chen and Gong, and new species of *Polycostatus* Ji and Barnes and *Rossodus*

Repetski and Ethington (Fig. 7). The introduction of these new faunal elements occurred within the lowest 5 ft (1.5 m) of the zone, so this thin zone is characterized by a very distinctive assemblage of taxa. However, the only species confined to this zone is *Iapetonudus ibexensis,* which occurs in only the lowest 3 ft (0.9 m) of the zone. The basal sample of the zone also contains three paraconodonts, *Problematoconites perforatus* Müller, *Westergaardodina bicuspidata* Müller, and *Westergaardodina polymorpha* Müller and Hinz; these genera are more typical of pre-Ibexian strata. Most other taxa except *Cordylodus proavus, Eoconodontus notchpeakensis,* and *Utahconus* n. sp. continue into the succeeding zone. Ranges of trilobites and brachiopods occurring in this zone are shown on Figure 8.

CORDYLODUS ANGULATUS ZONE

The *Cordylodus angulatus* Zone is the fifth conodont zone of the Skullrockian Stage. The base of the *Cordylodus angulatus* Zone is at the lowest occurrence of *Cordylodus angulatus* Pander. The top of the zone is at the base of the overlying *Rossodus manitouensis* Zone, at the lowest occurrence of *R. manitouensis* Repetski and Ethington or of *Loxodus bransoni* Furnish. This zone is in the upper (but not uppermost) part of the Barn Canyon Member.

The *Cordylodus angulatus* Zone has a diverse and characteristic conodont fauna. The lowest occurrences of *Cordylodus* n. sp., *Iapetognathus sprakersi* Landing, *Polycostatus oneotensis* (Furnish), *Scalpellodus* sp. aff. *S. gracilis* (Sergeeva), and *Variabiliconus bassleri* (Furnish) are within the *Cordylodus angulatus* Zone (Fig. 7). Nearly all taxa that originated in the underlying *Iapetognathus* Zone are found in this zone as well, but the ranges of *Iapetognathus fluctivagus* and *Paltodus* n. sp. end only slightly above the base of the *C. angulatus* Zone. The disappearance of *Iapetognathus fluctivagus* apparently is due to its evolutionary transition into a different species, *Iapetognathus sprakersi* Landing. The latter species and *Iapetognathus aengensis* (Lindström) occur only in this zone, although *I. aengensis* occurs in only one sample. *Cordylodus caseyi* Druce and Jones occurs only in this zone, but few elements have been identified. The ranges of *Cordylodus prion* Lindström, the robust *Teridontus* n. sp., and *Teridontus*? *expansus* terminate in this zone.

ROSSODUS MANITOUENSIS ZONE

The *Rossodus manitouensis* Zone is the sixth and youngest zone of the Skullrockian Stage, and it extends into the lowest strata of the overlying Stairsian Stage of the Ibexian Series. The base of the *Rossodus manitouensis* Zone is at the lowest occurrence of *R. manitouensis,* which is at sample LCM-HL518 at Lawson Cove (Table 5). The lowest occurrence of *Loxodus bransoni* is only 1 ft (0.3 m) higher (sample LCM-HL519), but in some sections in the Ibex area *L. bransoni* occurs slightly below *R. manitouensis.* In such sections the base of the zone is placed at the lowest occurrence of *L. bransoni,* which is used to name a new subzone of this zone, discussed below. *Leucorhinion ambonodes* Landing also occurs at the base of this zone in Section A and in the Lange Ranch section, Texas. The lowest occurrence of *Clavohamulus densus* Furnish is slightly above the base of this zone in several sections in the Ibex area. *Rossodus* sp. aff. *R. manitouensis* also occurs abundantly in the lower part of this zone. This taxon has a slightly different M element from *R. manitouensis* sensu stricto, but otherwise the species are identical. All of these species are good indicators of the lowest part of the *R. manitouensis* Zone, which is present at Lava Dam North, Section A, and in the Drum Mountains. The base of the zone at Sevier Lake Corral South is just above a fault at SCS-203, and the lowest beds of the zone are faulted out.

The *Rossodus manitouensis* Zone includes all House Limestone strata above the *Cordylodus angulatus* Zone, more than half the thickness of the formation. The highest strata of the middle segment of the Lawson Cove section are referred to this zone (Fig. 7, Table 5). All strata of the upper segment of the section are also referred to this zone (Fig. 9, Table 6). Based on comparison with the Lava Dam North section, the top part of the *R. manitouensis* Zone is missing from the Lawson Cove section because the top of the House Limestone has been removed by erosion. The thickness of the incomplete *R. manitouensis* Zone at Lawson Cove is 186 ft (56.7 m), and the thicker but still incomplete zone at Lava Dam North is 334 ft (101.8 m), making this the thickest biozonal unit considered in this report. This zone in the upper segment of the Lawson Cove section includes the uppermost part of the Barn Canyon Member, all of the Burnout Canyon Member, and all of the Red Canyon Member of the House Limestone. At Lava Dam North the *Rossodus manitouensis* Zone continues through all of the Red Canyon Member and the lowermost 5 ft (1.5 m) of the Fillmore Formation at the top of the exposure (Fig. 10). At the 1965 C section the lower 13 ft (4.0 m) of the Fillmore Formation is assigned to this zone, which includes ca. 7–8 ft (2.1–2.4 m) of strata above the top of the Lava Dam North section. The composite thickness of the *R. manitouensis* Zone at Lava Dam North and the 1965 C section is ca. 343 ft (104.5 m). The ranges of many conodont taxa found in this zone end slightly below the top of the zone in the Upper House Limestone or at the top of the zone in the lower Fillmore (Ethington and Clark, 1981; Ethington et al. (1987).

The conodont fauna of this zone is abundant and diverse and includes the culmination of several evolutionary lineages. Many species have lowest occurrences in this zone and range through various intervals of strata at Lawson

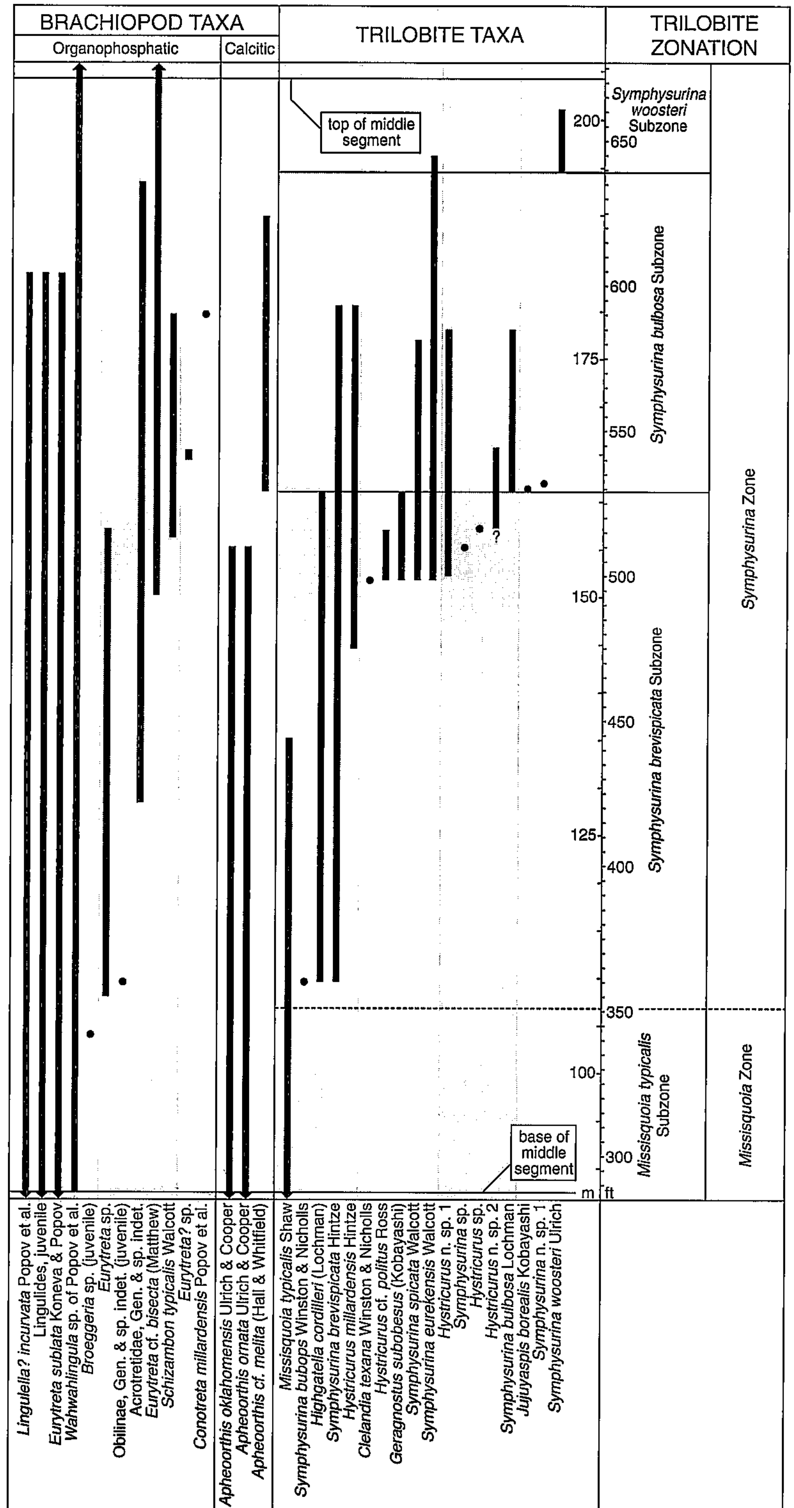


Figure 8. Ranges of brachiopod and trilobite taxa and derived trilobite biostratigraphic units in the middle segment of the Lawson Cove section. Ranges of conodonts from the middle segment are shown on Figure 7. For detailed occurrence data, see Table 5 on CD-ROM.

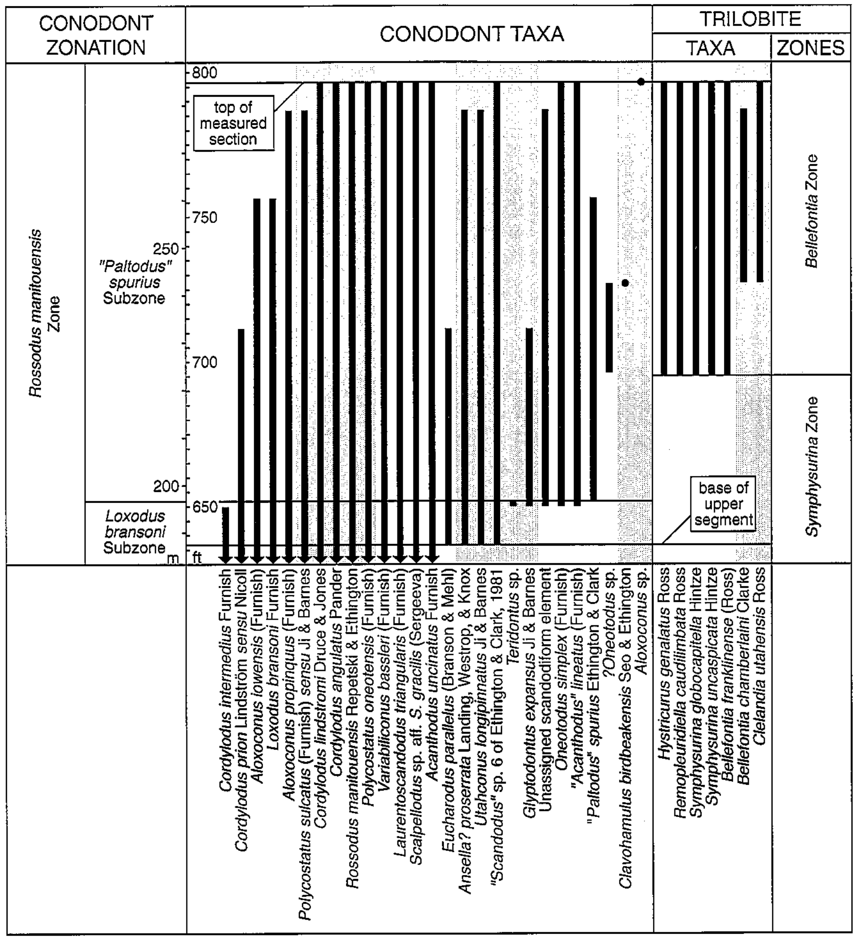


Figure 9. Ranges of conodont and trilobite taxa and derived biostratigraphic units in the upper segment of the Lawson Cove section. For detailed occurrence data, see Table 6 on CD-ROM.

Cove (Figs. 7, 9–11); these species include *Acanthodus lineatus* (Furnish), *Ansella? proserrata* Landing, Westrop, and Knox, *Clavohamulus densus* Furnish, *Clavohamulus* sp., *Eucharodus parallelus* (Branson and Mehl), *Glyptoconus expansus* Ji and Barnes, *Laurentoscandodus triangularis* (Furnish), *Loxodus bransoni, Oneotodus simplex* Furnish, ?*Oneotodus* sp., "*Paltodus*" *spurius* Ethington and Clark, *Polycostatus sulcatus* (Furnish), *Rossodus manitouensis,* "*Scandodus*" sp. 6 of Ethington and Clark 1981, *Teridontus* sp., ?*Tropodus* sp., unassigned scandodiform elements, *Utahconus longipinnatus* Ji and Barnes, and *Variabiliconus transiapeticus* Löfgren, Repetski, and Ethington. Several species have single occurrences within the zone, including *Aloxoconus* sp., *Clavohamulus birdbeakensis* Seo and Ethington, *Clavohamulus* sp., *Iapetognathus aengensis* (Lindström), and *Scolopodus* sp.

Ethington and Clark (1981) used the term "*Loxodus bransoni* Interval" for strata that are referred to the *Rossodus manitouensis* Zone of this report, and they considered that *L. bransoni, Clavohamulus densus,* and *R. manitouensis* were among the taxa that characterized their "Interval." The *Rossodus manitouensis* Zone is quite thick, and we are now able to recognize two subzones of quite unequal thickness; the lower, rather thin *Loxodus bransoni* Subzone and the upper, much thicker "*Paltodus*" *spurius* Subzone. The boundary between these subzones is at the lowest occurrence of "*Paltodus*" *spurius,* and both subzones are recognized in all sections (Lawson Cove, Lava Dam North, Sevier Lake Corral, Section A, and Drum Mountains) where we have conodont collections from the appropriate stratigraphic interval. We also recognize these subzones in some other areas, such as in the Manitou Formation of Colorado and

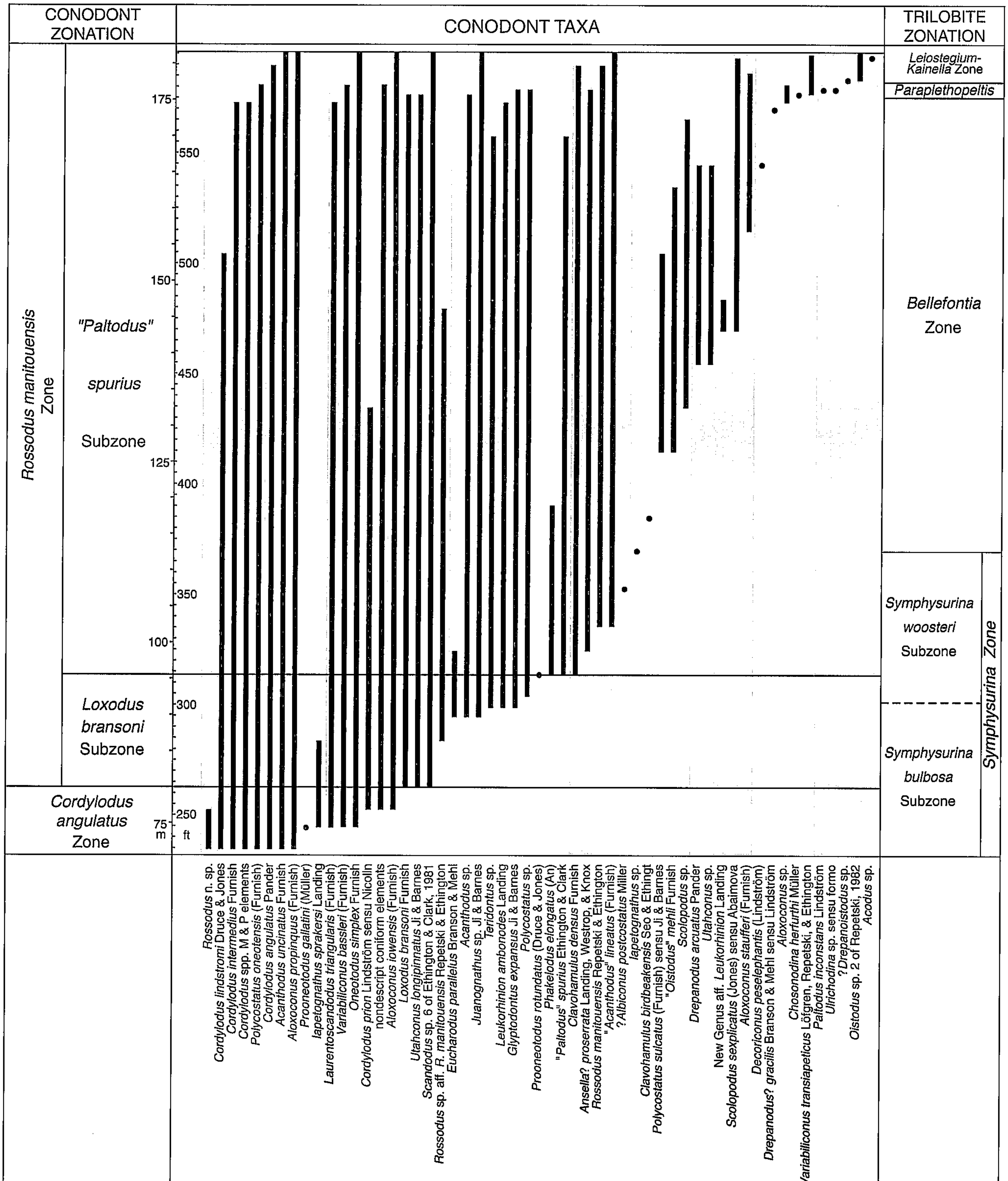


Figure 10. Ranges of conodont taxa and derived biostratigraphic units in the upper part of the Lava Dam North section. Ranges of brachiopods and trilobites are shown on Figure 12. For detailed occurrence data, see Table 7 on CD-ROM.

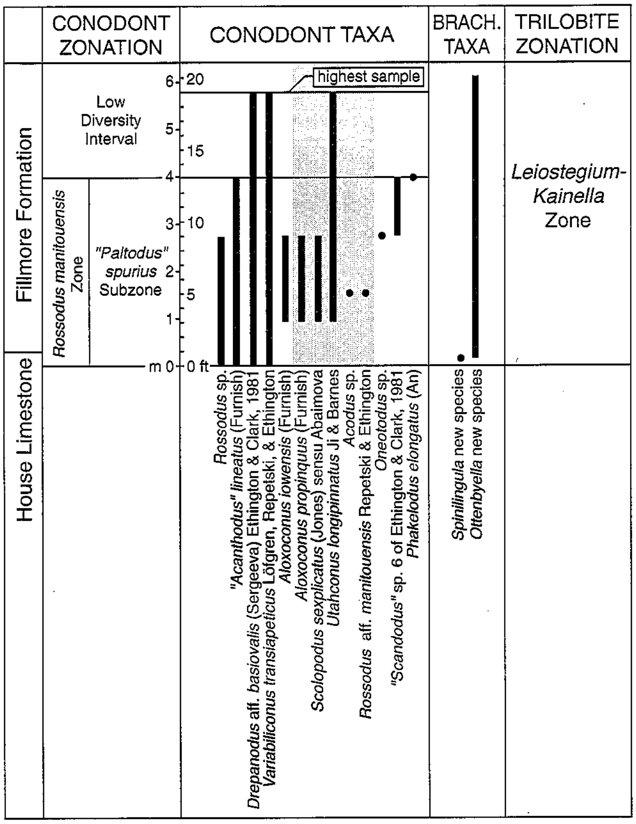


Figure 11. Ranges of conodont and brachiopod taxa and derived biostratigraphic units in the 1965 C section. For detailed occurrence data, see Table 8 on CD-ROM. BRACH. TAXA = Brachiopod Taxa.

the Tanyard Formation in Texas, but the geographic distribution of "*Paltodus*" *spurius* may be somewhat limited. For example, this species is too rare in strata deposited in the Oklahoma Aulacogen to be useful for recognizing these subzones.

Loxodus bransoni Subzone (New)

The *Loxodus bransoni* Subzone is the lower subzone of the *Rossodus manitouensis* Zone. The subzone is characterized by the presence of taxa such as *Rossodus manitouensis*, *R.* sp. aff. *manitouensis*, *Leucorhinion ambonodes*, *Loxodus bransoni*, and *Clavohamulus densus* and by the absence of "*Paltodus*" *spurius*. The base of the subzone is at the base of the *R. manitouensis* Zone and is placed at the lowest occurrence of either *R. manitouensis* or *Loxodus bransoni*, whichever is lower. In the middle segment of the Lawson Cove section, the base of the subzone is in sample LCM-HL518, in the upper part of the Barn Canyon Member (Table 5). The top of the subzone is at the base of the "*Paltodus*" *spurius* Subzone, at the lowest occurrence of "*P.*" *spurius*. In the middle segment of the Lawson Cove section, this horizon is in sample LCM-HM564, 13 ft (4.0 m) above the base of the Burnout Canyon Member. The base of the subzone is below the base of the upper segment of the Lawson Cove section, but in that segment the top of the subzone is in sample LCU-HM15, 15 ft (4.6 m) above the base of the Burnout Canyon. The subzone base is at sample LDN-273 at Lava Dam North, sample A-251 at Section A, and at sample DM-487 in the Drum Mountains. The lower part of the subzone is faulted out at Sevier Lake Corral South, but the subzone begins at SCS-203 and extends to SCS-209.

This subzone occurs in the uppermost part of the Barn Canyon Member and in the lower part of the Burnout Canyon Member, near the middle of the House Limestone (Table 9). An exception is in the Drum Mountains section, where the top of the subzone is at the top of the Barn Canyon. However, the underlying 20 ft (DM-467 to 487; unit 20) is poorly exposed and might actually represent the lower beds of the Burnout Canyon Member. The *Loxodus bransoni* Subzone is 46 ft (14.0 m) thick in the middle segment of the Lawson Cove section, 51 ft (15.5 m) at Lava Dam North, 53 ft (16.2 m) at Section A, and 36 ft (11.0 m) thick in the Drum Mountains sections, where it may be incompletely sampled at the base (Table 9).

"*Paltodus*" *spurius* Subzone (New)

The "*Paltodus*" *spurius* Subzone is the upper subzone of the *Rossodus manitouensis* Zone and comprises most of the zone. The subzone is characterized by most of the common taxa of the underlying *Loxodus bransoni* Subzone as well as by the presence of "*Paltodus*" *spurius*. The base of the subzone is at the lowest occurrence of "*Paltodus*" *spurius*, which is in sample LCM-HU570 in the middle segment at Lawson Cove (Table 5) and at LCU-HU15 in the upper segment (Table 6). The top of the Lawson Cove section is within this subzone. More of this thick subzone is present at Lava Dam North, where the base is at sample LDN-324, within the Burnout Canyon Member. At Lava Dam North this subzone includes the Red Canyon Member of the House Limestone and the lower 5 ft (1.5 m) of the Fillmore Formation (Fig. 10, Table 7). The top of the subzone and top of the *Rossodus manitouensis* Zone are represented only at the 1965 C section, where this boundary is at sample 1965C-14 (Fig. 11, Table 8). Based on a composite thickness from Lava Dam North and the 1965 C section, the "*P.*" *spurius* Subzone is ca. 292 ft (86.0 m) thick. The lower 43 ft (13.1 m) of this interval is present at the top of the Sevier Lake Corral South section, from SCS-209 to SCS-245 (Table 9). The top 9 ft (2.7 m) of strata in our described section at Section A contain "*Paltodus*" *spurius*, but our collections do not extend high enough to document the top of the subzone.

Nearly all of the conodont species that occur in the "*Paltodus*" *spurius* Subzone have their highest occurrences in the uppermost House Limestone or in the lower 13 ft (4.0 m) of the Fillmore Formation. Younger strata contain a much less diverse fauna that is assigned to the Low Diversity Interval (Fig. 11). Ross et al. (1997) placed the top of the Skullrockian Stage at the top of the *Paraplethopeltis* Trilobite Zone, slightly below the top of the House Limestone (Fig. 12). This horizon is below the top of the "*Paltodus*" *spurius* Subzone, so the top of this subzone extends into the base of the Stairsian Stage.

Closely spaced samples from the upper ca. 20 ft (ca. 6 m) of the House Limestone and the lower ca. 20 ft (ca. 6 m) of the Fillmore Formation produced interesting data that may be of biostratigraphic utility in the future. Figures 10 and 11 show that a new fauna appears near the top of the "*Paltodus*" *spurius* Zone at Lava Dam North and at 1965 C. The taxa include single occurrences of *Chosonodina herfurthi* Müller, *Paltodus inconstans* Lindström (a North Atlantic Faunal Realm species) and ?*Ulrichodina* sp. sensu formo, as well as the lowest occurrences of *Variabiliconus transiapeticus*, "*Scandodus*" sp. 6 of Ethington and Clark (1981), and *Drepanoistodus* aff. *basiovalis* (Sergeeva) as treated by Ethington and Clark (1981). Slightly higher are occurrences of other taxa placed in open nomenclature. Several of these taxa continue into the lower beds of the Fillmore Formation (Fig. 11), where some disappear near the top of the *Rossodus manitouensis* Zone. *Drepanodus* aff. *basiovalis*, *Utahconus longipinnatus*, and *Variabiliconus transiapeticus* continue into younger strata assigned to the Low Diversity Interval.

Based on the occurrence of this new fauna, it may be possible to recognize a new subzone of the *Rossodus manitouensis* Zone in these uppermost House and the lowermost Fillmore strata. Some of the taxa that occur in this interval are undescribed, and the fauna is not known from enough other localities to justify recognizing a new subzone at this time. The lowest occurrence of this fauna is in the first sample above a sequence boundary and may eventually serve to characterize and correlate Sequence 13 (Fig. 3), which is discussed in the section of this report on Sequence Stratigraphy.

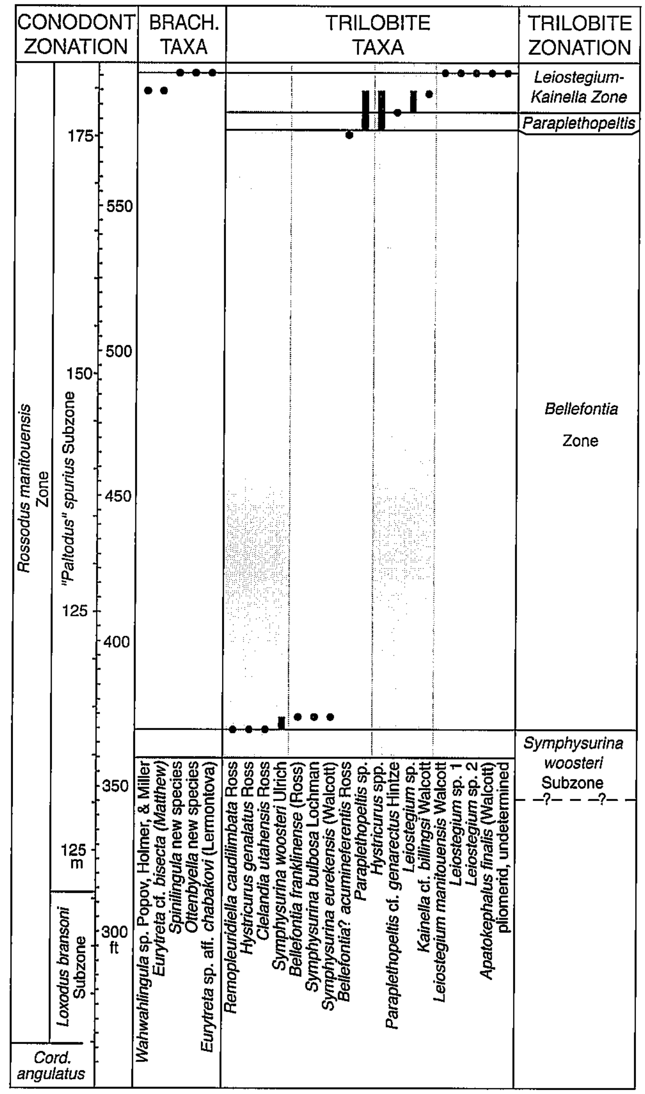


Figure 12. Ranges of trilobite and brachiopod taxa and derived biostratigraphic units in the upper part of the Lava Dam North section. Ranges of conodonts from this section are shown on Figure 10. For detailed occurrence data, see Table 7 on CD-ROM. BRACH TAXA = Brachiopod Taxa.

LOW DIVERSITY INTERVAL

The mass extinction of conodonts at the top of the *Rossodus manitouensis* Zone resulted in a greatly impoverished conodont fauna in overlying strata. This extinction occurs at 14 ft (4.3 m) in the 1965 C section, 13 ft (4.0 m) above the base of the Fillmore Formation. Overlying strata have a fauna that does not include the abundant, richly diverse fauna found in the *R. manitouensis* Zone, but the fauna instead is one of low abundance and low taxonomic diversity. This interval of strata is conspicuous because of the paucity of its conodont fauna and is named the Low Diversity Interval. In the Ibex area this biozonal unit is present only in the 1965 C section, and we have studied only the lower part (Table 9) of the complete interval, which was documented by Ethington and Clark (1981). Ethington et al. (1987, Fig. 8.3) discussed this faunal turnover and reported ranges of conodont species in the lower part of the Low Diversity Interval from a section located between the Lava

Dam North and 1965 C sections. They reported *Drepanoistodus* sp., ?*Oneotodus* sp., ?*Scandodus* sp. 6 of Ethington and Clark from near the bottom of the interval, and they also reported *Acodus* sp. and *Eucharodus parallelus* from a somewhat higher level.

Table 7 and Figure 10 document taxa that we recovered from the upper House and basal Fillmore at Lava Dam North. Table 8 and Figure 11 document taxa that we recovered in new collections from the lower beds of the Fillmore at the 1965 C section. Many characteristic taxa of the *Rossodus manitouensis* Zone occur in the upper House as high as sample LDN-583, and others extend to LDN-591.5 (Fig. 10). Sample LDN-593 and younger samples have greatly reduced abundance and diversity. This low diversity occurs also in the lowest sample at the 1965 C section, at the top of the House Limestone. Samples 1965C-4 to 1965C-10 show greater abundance and diversity (up to 10 species), but the next sample, 1965C-12, has only one conodont element. Sample 1965C-14 has six species, but the next samples have only three. We place the base of the Low Diversity Interval at the level of sample 1965C-14, and this horizon is 2.5 ft (0.8 m) above an important sequence boundary that is discussed in a later section of this report. The Low Diversity Interval extends somewhat higher in the Fillmore, but we studied only the lowest part so as to document completely the faunal turnover at the top of the *Rossodus manitouensis* Zone. This faunal turnover is considered more fully in the discussion of Sequence 13 in the section on Sequence Stratigraphy.

TRILOBITE BIOSTRATIGRAPHY

J. D. Loch, J. H. Stitt, and J. F. Miller

INTRODUCTION

The Utah trilobite zonation employed in this report is based on collections published by other authors in the lowest strata discussed, on sparse collections in somewhat younger strata, and on new collections for the middle and upper part of the interval. Hintze and Palmer (1976) discussed the oldest strata that we studied in the Ibex area, the upper members of the Orr Formation. They reported trilobite identifications that are summarized on Figure 2. Hintze et al. (1988) and Ross et al. (1997) discussed the trilobite biostratigraphy of the Notch Peak, House, and Fillmore formations. The trilobite zonation that they recognized in these strata is readily applicable to the same strata in the Lawson Cove and Lava Dam North sections (Figures 2, 3).

Collecting in the Lava Dam Member of the Notch Peak Formation and the House Limestone in the Lawson Cove section located 50 beds that have yielded ca. 1780 trilobite cranidia, pygidia, and librigenae. The lowest collections from Lawson Cove include trilobites diagnostic of the *Saukiella serotina* Subzone of the *Saukia* Zone, assigned to the Sunwaptan Stage. Higher collections include trilobites assigned to the *Eurekia apopsis, Missisquoia, Symphysurina,* and *Bellefontia* Zones of the Skullrockian Stage of the Ibexian Series (Ross et al., 1997). Several new collections from the highest beds of the House Limestone and the lowest beds of the Fillmore Formation at the Lava Dam North section are assigned to the *Paraplethopeltis* Zone at the top of the Skullrockian Stage and to the *Leiostegium-Kainella* Zone at the base of the Stairsian Stage (Ross et al., 1997). These trilobites allow correlation of this interval in the Lawson Cove and Lava Dam North sections with coeval strata in the Great Basin, Canadian Rocky Mountains, Texas, Oklahoma, the Upper Mississippi Valley, and selected areas in the eastern United States (see Hintze et al., 1988, p. 16–20, and Ross et al., 1997, p. 29–31 for recent summaries).

Most of the trilobite biozonal units were recognized originally in Utah (Ross, 1951; Hintze, 1953), Texas (Winston and Nicolls, 1967; Longacre, 1970) and Oklahoma (Stitt, 1971b; 1977; 1983). J. H. Stitt and J. F. Miller used published data and new collections from the Threadgill Creek and Lange Ranch sections in Texas (Fig. 13) to develop the trilobite zonation shown on Figure 14. There are some differences in the zonal classification in Texas and Utah, which are noted below.

ELVINIA ZONE

The *Elvinia* Zone is widespread in North America and is well known in the Great Basin (Palmer, 1965) and in Texas (Barnes and Bell, 1977). Hintze and Palmer (1976) reported *Elvinia* Zone trilobites from the Steamboat Pass Shale and Sneakover Limestone members of the Orr Formation in the Lawson Cove Reservoir section, Wah Wah Mountains. They reported faunas from this zone in the Corset Spring Shale and Sneakover Limestone members in the Orr Ridge area of the central House Range.

IRVINGELLA MAJOR ZONE

This zone was originally considered as the upper subzone of the *Elvinia* Zone, but Palmer (1998) considered it as a zone and placed the base of the Sunwaptan Stage at its base (Figs. 2, 14).

TAENICEPHALUS ZONE

The *Taenicephalus* Zone is also well known in the Great Basin due to the work of Palmer (1965). Hintze and Palmer (1976) reported faunas assigned to this zone from the middle to upper parts of the Sneakover Pass Limestone Member in several sections, including Lawson Cove Reservoir and

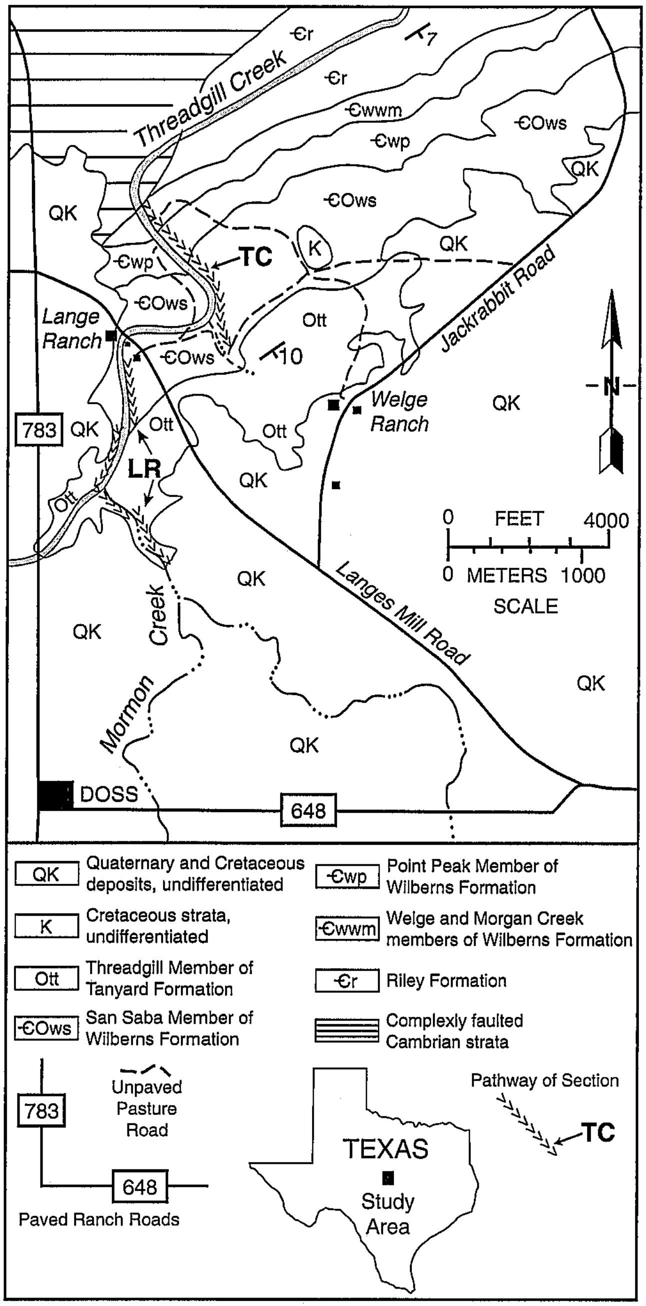


Figure 13. Geologic sketch map showing location of Threadgill Creek (TC) and Lange Ranch (LR) sections in southwest part of Llano Uplift, Central Texas.

Orr Ridge. Hintze et al. (1988, p. 17) reported *Taenicephalus* sp. from 67 ft (20.4 m) above the base of the Hellnmaria Member of the Notch Peak Formation; this collection was made by J. F. Miller in the Steamboat Pass area of the southern House Range.

SARATOGIA ZONE

The *Saratogia* Zone is known from one small collection from 3 ft (0.9 m) above the base of the Chalk Knolls North section. Bob Pody identified *Ptychaspis* sp. and *Richardsonella* sp. in this collection, which is from the middle part of the Hellnmaria Member of the Notch Peak Formation (Fig. 5).

IDAHOIA AND *ELLIPSOCEPHALOIDES* ZONES

The *Saratogia* Zone is not recognized in Texas, and strata between the *Taenicephalus* and *Saukia* zones (Fig. 14) are instead assigned to the *Idahoia* and *Ellipsocephaloides* zones.

SAUKIA ZONE

The *Saukia* Zone previously was divided into four subzones, but the highest subzone is now the *Eurekia apopsis* Zone, which is discussed separately below. The three remaining subzones are the *Saukiella pyrene, S. junia,* and *S. serotina* subzones. J. F. Miller and J. H. Stitt made new collections from the Threadgill Creek section in Texas that resulted in altering the subdivision of the *Saukia* Zone (see discussion by Stitt and Straatman, 1997). The base of the *Saukia* Zone is now well below the base of the *Saukiella pyrene* Subzone, which is the lowest named subzone. As a result, the lowest interval of the *Saukia* Zone is assigned informally to an "unnamed interval" (Fig. 14), which is characterized by the presence of *Ptychopleurites spinosa* Stitt and Straatman, *Rasettia capax* (Billings), *Monocheilus truncatus* Ellinwood, and a new species of *Briscoia.* All have lowest occurrences at 1139 ft (347.2 m) in the Threadgill Creek section, Texas, and the revised base of the *S. pyrene* Subzone is at 1205 ft (367.3 m) at Threadgill Creek.

The lower part of the *Saukia* Zone is poorly known in the Great Basin and has never been reported from the Notch Peak Formation. We report one collection assigned to the *Saukiella pyrene* Subzone from the Chalk Knolls Middle section, at 910 ft (277.4 m) in the measured traverse and 7 ft (2.1 m) below the top of the Hellnmaria Member. Bob Pody made this collection and identified *Saukiella pyrene* (Walcott) and *Plethometopus convergens* (Raymond). Both species occur in this subzone in Texas (Longacre, 1970), and the latter species occurs in the coeval *Rassettia magna* Subzone in the Oklahoma aulacogen (Stitt, 1977).

Hintze et al. (1988, p. 17, Table 4) reported the *Saukiella junia* Subzone in the Red Tops Member in the Steamboat Pass section. Hintze et al. (1988, p. 17) pointed out that the stratigraphic position of the *Saukiella junia-Saukiella serotina* Subzone boundary is not well established in the

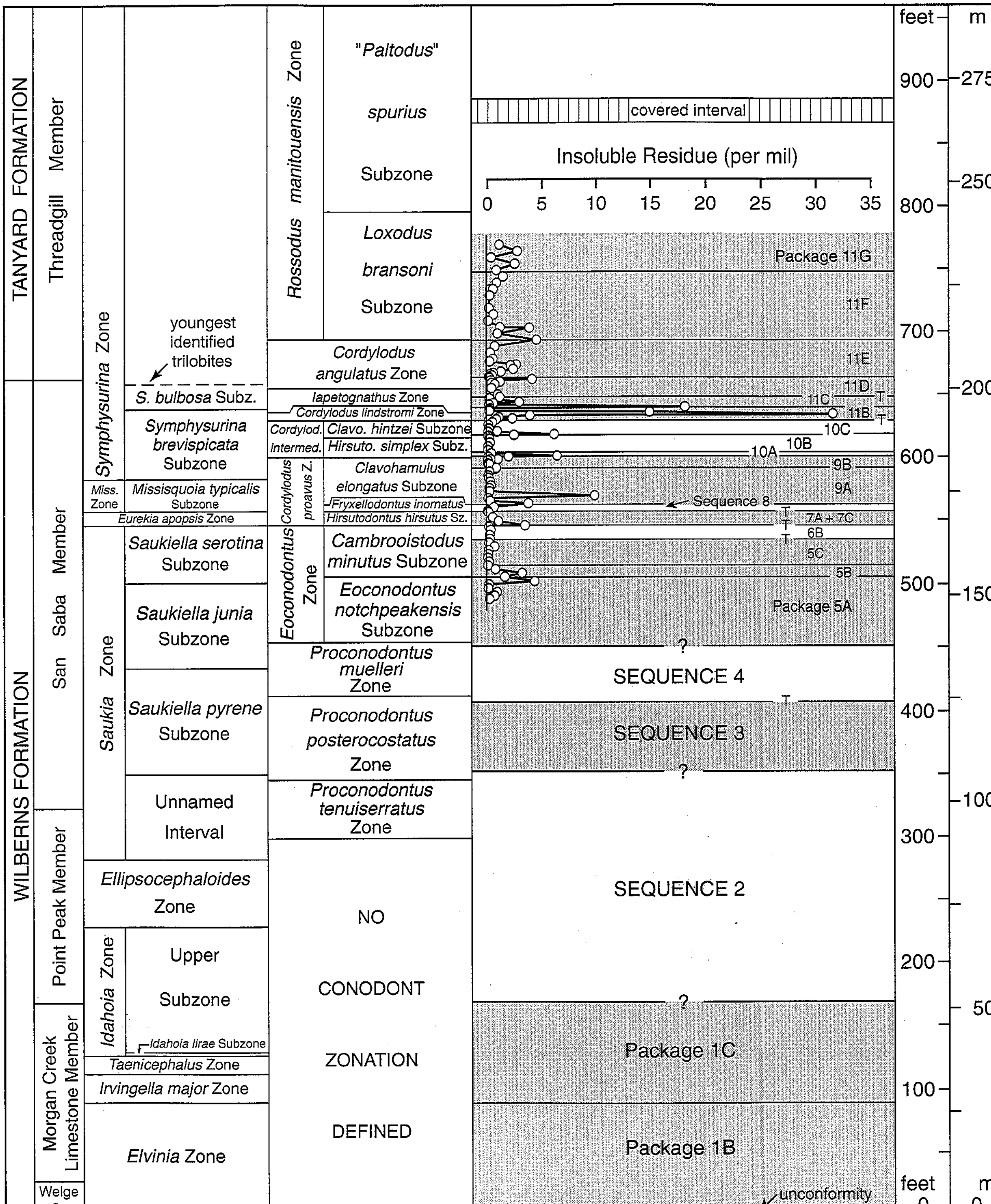


Figure 14. Summary of composite Threadgill Creek-Lange Ranch section in Central Texas showing lithostratigraphic, biostratigraphic, and sequence stratigraphic units. Odd-numbered sequences are shaded. Curve shows variation in concentration of light fraction (specific gravity < ca. 2.87) of insoluble residues of conodont samples; material is mostly fine quartz sand. For original data, see Table 21. Compare with similar insoluble residue curves shown on Figures 16 and 17 for Utah strata. T = truncation surface at sequence or package boundary.

Ibex area. Some collections from the upper Red Tops and lower Lava Dam members in the southern House Range are questionably referred to the *Saukiella serotina* Subzone based on conodont-based correlations between Utah, Texas, and Oklahoma. Collections from 55 ft (16.8 m) above the base of the Lava Dam Member (and from higher collections) at Lava Dam Five contain *Euptychaspis kirki*, a taxon that is restricted to this subzone (Hintze et al., 1988, Table 4).

The *Saukiella serotina* Subzone is also known from the Lawson Cove section. Trilobites characteristic of the *Saukiella serotina* Subzone are present in collections from LCL-LD110 to LCL-LD158 from the Lava Dam Member (Fig. 6). Taxa include *Euptychaspis kirki, Eurekia eos* (Hall), *Stenopilus latus* Ulrich, *Bayfieldia simata* Winston and Nicholls, and *Rasettia wichitaensis* (Resser) (Plate 1, Table 4). These collections come from the middle and upper part of the *S. serotina* Subzone.

A major extinction event occurred at the top of the *Saukiella serotina* Subzone (= base of *Eurekia apopsis* Zone). Almost all species and genera of this large, abundant,

PLATE 1

Representative trilobites from the *Saukiella serotina* Subzone and the *Eurekia apopsis, Missisquoia,* and *Symphysurina* zones. All figured specimens from Lawson Cove section except Figures 25–27, which are from Lava Dam North section, sample at 196.5 ft. Section segment and footage are given and correspond to samples recorded in Tables 6 and 7 on CD-ROM. All specimens housed at the University of Missouri-Columbia (UMC).

1. *Eurekia eos* Ulrich. Cranidium, LCL-LD113, UMC 17473, x3.

2. *Eurekia apopsis* (Winston and Nicholls). Cranidium, LCL-LD165, UMC 17474, x3.

3, 4. *Plethopeltis arbucklensis* Stitt. 3, cranidium, LCL-LD183, UMC 17475, x4; 4, pygidium, LCL-LD183, UMC 17476, x4.

5. *Apoplanius rejectus* Lochman. Cranidium, LCL-LD196, UMC 17477, x13.

6. *Missisquoia typicalis* Shaw. Cranidium, LCM-HL352, UMC 17478, x10.

7. *Highgatella cordilleri* (Lochman). Cranidium, LCM-LD275, UMC 17479, x8.

8–10. *Symphysurina brevispicata* Hintze. 8, cranidium, LCM-HL490, UMC 17480, x8; 9, pygidium, LCM-HL490, UMC 17481, x5.5; 10, librigena, LCM-HL490, UMC 17482, x9.

11. *Hystricurus millardensis* Hintze. Cranidium, LCM-HL437, UMC 17483, x5.

12–14. *Symphysurina eurekensis* (Walcott). 12, cranidium, LCM-HL478, UMC 17484, x3; 13, pygidium, LCM-HL478, UMC 17485, x2; 14, librigena, LCM-HL478, UMC 17486, x4.

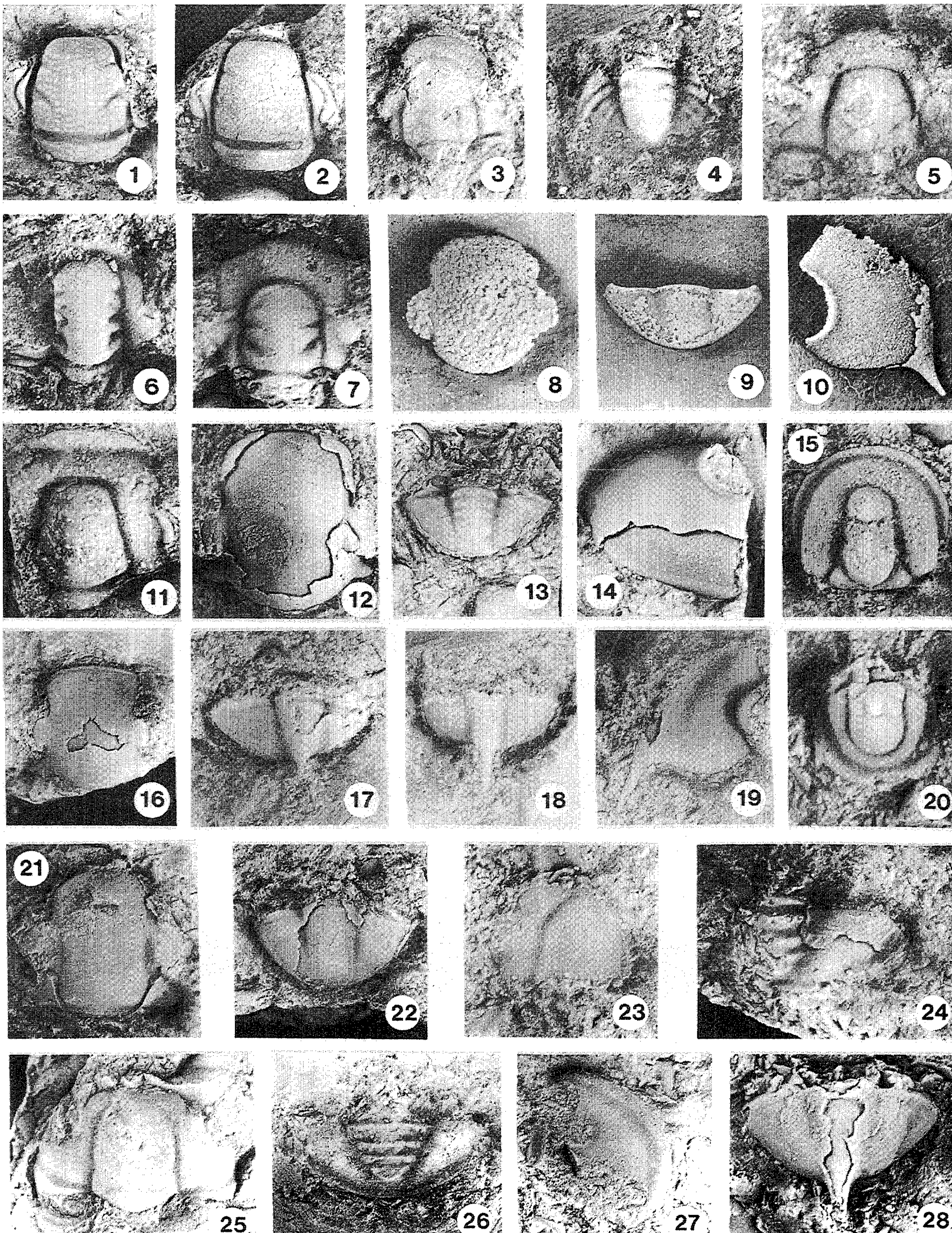
15, 20. *Geragnostus subobesus* (Kobayashi). 15, cranidium, LCM-HL406, UMC 17487, x9; 20, pygidium, LCM-HL406, UMC 17488, x10.

16–19. *Symphysurina spicata* Walcott. 16, cranidium, LCM-HL411, UMC 17489, x3; 17, pygidium, right pleural region incompletely preserved, LCM-HL411, UMC 17490, x4; 18, pygidium, LCM-HL424, UMC 17491, x4; 19, librigena, LCM-HL411, UMC 17492, x4.

21, 22. *Symphysurina bulbosa* Lochman. 21, cranidium, LCM-HL535, UMC 17493, x4; 22, pygidium, LCM-HL535, UMC 17494, x4.

23–27. *Jujuyaspis borealis* Kobayshi. 23, fragmentary cranidium, LCM-HL438, UMC 17495, x5; 24, fragmentary pygidium, LCM-HL438, UMC 17496, x6; 25, cranidium, Lava Dam North (LDN) section 196.5, UMC 17497, x3.5; 26, pygidium, LDN 196.5, UMC 17498, x3; 27, librigena, LDN 196.5, UMC 17499, x3.5.

28. *Symphysurina woosteri* Walcott. Pygidium, LCM-HM559, UMC 17500, x6.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diverse, and long-ranging trilobite fauna and the conodont fauna of the *Cambrooistodus minutus* Subzone were extinguished at or just below this horizon (Miller et al., 1982). Only a few trilobite taxa from the *S. serotina* Subzone range upward into the *E. apopsis* Zone in Texas (Longacre, 1970), Oklahoma (Stitt, 1971b, 1977), Utah (Hintze et al., 1988), and the Canadian Rocky Mountains (Ludvigsen, 1982; Westrop, 1986; Loch et al., 1993). No brachiopod species and only one genus known from the *S. serotina* Subzone or lower occurs above the base of the *E. apopsis* Zone (Freeman and Stitt, 1996).

EUREKIA APOPSIS ZONE

The base of the zone is defined by the lowest occurrence of *Eurekia apopsis* (Winston and Nicholls) (Plate 1, Table 4), *Apatokephaloides clivosus* Raymond, or *Larifugula leonensis* (Winston and Nicholls). These species occur at Lawson Cove in collections LCL-LD163, LCL-LD165, and LCL-LD178 in the Lava Dam Member (Fig. 6). The base of the zone in the Ibex area and in other areas in North America is at or slightly above the lowest occurrence of conodonts that define the base of the *Cordylodus proavus* Zone (Hintze et al., 1988, Figure 4; Ross et al., 1997, Figure 10). In the Lawson Cove section, the *Cordylodus proavus* Zone begins at LCL-LD158, suggesting that with additional collecting the base of the *Eurekia apopsis* Zone may be revised to a position roughly five feet (1.5 m) lower in the section. The top of the *E. apopsis* Zone marks another extinction horizon.

MISSISQUOIA ZONE

Initially proposed by Winston and Nicholls (1967), this zone was redefined by Derby et al. (1972) to include the interval between the lowest occurrence of species of *Missisquoia* Shaw and the lowest occurrence of species of *Symphysurina* Ulrich. Stitt (1977) defined two subzones in the *Missisquoia* Zone, a lower *Missisquoia depressa* Subzone and an upper *Missisquoia typicalis* Subzone. The base of the *Missisquoia* Zone was previously taken as the base of the Ordovician in North America (following Winston and Nicholls, 1967).

The *Missisquoia depressa* Subzone can be recognized in the Lava Dam Member by the occurrence of abundant specimens of *Plethopeltis arbucklensis* Stitt in collections LCL-LD182 and LCL-LD183 (Fig. 6). The base of the *Missisquoia* Zone in the nearby Lava Dam Five section coincides with the lowest occurrence of *Cordylodus proavus* Müller. The lowest occurrence of *Cordylodus proavus* in the Lawson Cove section is also in collection LCL-LD182, indicating that the specimens of *P. arbucklensis* come from the base of the *M. depressa* Subzone. This subzone is missing in the Threadgill Creek and Lange Ranch sections, Texas, although the *M. typicalis* Subzone is present.

The base of the *Missisquoia typicalis* Subzone is defined by the lowest occurrence of the trilobites *M. typicalis* Shaw or *Apoplanias rejectus* Lochman (Stitt, 1977; Ross et al., 1997). This horizon often coincides with the lowest occurrence of the orthid brachiopods *Apheoorthis ornata* Ulrich and Cooper or *Apheoorthis oklahomensis* Ulrich and Cooper (Freeman and Stitt, 1996). In the Lawson Cove section, *M. typicalis, A. ornata,* and *A. oklahomensis* have their lowest occurrence in collection LCL-LD192, and *Apoplanius rejectus* occurs in LCL-LD196 (Plate 1, Table 4). The lowest occurrence of the conodonts that define the base of the *Fryxellodontus inornatus* Subzone of the *Cordylodus proavus* Zone occur at or very close to the base of the *M. typicalis* Subzone (Hintze et al., 1988, Figure 4; Freeman and Stitt, 1996). The lowest occurrence of *F. inornatus* in the Lawson Cove section is at LCL-LD191 (Fig. 6), indicating that the lowest collections of *M. typicalis, Apheoorthis ornata,* and *A. oklahomensis* occur at the base of the *M. typicalis* Subzone, and *Apoplanius rejectus* occurs slightly above the base of the subzone. An additional collection of *M. typicalis* [together with *Missisquoia enigmatica* (Kobayashi)] occurs near the top of the subzone in sample LCL-LD284. *M. typicalis* ranges into the overlying *Symphysurina* Zone in the Lawson Cove section, just as it does in Oklahoma (Stitt, 1977).

SYMPHYSURINA ZONE

Hintze (1953) named the *Symphysurina* Zone for trilobites occurring in the upper part of the Notch Peak Formation and the lower part of the House Limestone. Stitt (1977) divided the *Symphysurina* Zone into three subzones in Oklahoma, a lower *Symphysurina brevispicata* Subzone, a middle *Symphysurina bulbosa* Subzone, and an upper *Symphysurina woosteri* Subzone, all of which can be recognized in the Lawson Cove section (Loch et al., 1999).

At Lawson Cove the base of the *Symphysurina brevispicata* Subzone is defined by the lowest occurrence of *Highgatella cordilleri* (Lochman) near the top of the Lava Dam Member in collection LCL-LD287, 9 feet (2.7 m) below the base of the House Limestone. A coquina of specimens of *Symphysurina bubops* Winston and Nicholls, *Highgatella cordilleri,* and *Symphysurina brevispicata* occurs in collection LCM-LD275, less than one foot (0.3 m) below the base of the House in the middle segment of the Lawson Cove section. This coquina is widespread in the Ibex area and forms a convenient biostratigraphic marker and a lithostratigraphic key bed for the Notch Peak-House contact. The *S. brevispicata* Subzone is 170 feet (51.5 m) thick in the Lawson Cove section and includes twelve collections. Additional taxa that occur in the *S. brevispicata* Subzone (Plate 1, Figs. 6, 8) include *Clelandia texana* Winston and Nicholls, *Geragnostus subobesus* (Kobayashi), *Hystricurus millardensis* Hintze, *Hystricurus* cf. *H. politus* Ross, *Missisquoia enigmatica* (Kobayashi), *Missisquoia inflata* Winston and Nicholls, *Missisquoia typicalis* Shaw, *Symphysurina eurekensis* (Walcott), *Symphysurina spicata* Hintze, and two new species of *Hystricurus*. This subzone is also known from central Texas (Miller and Stitt, 1995) (Fig. 14).

The youngest trilobite collections at the Lange Ranch section in Texas are assigned to the *Symphysurina bulbosa* Subzone (Miller and Stitt, 1995), and it is also present in Utah sections. The base of the *S. bulbosa* Subzone is defined by the lowest occurrence of *Symphysurina bulbosa* Lochman, which occurs in collection LCM-HL437, 161 feet (48.8 m) above the base of the House Limestone. Many trilobites from the underlying *Symphysurina brevispicata* Subzone range upward into the *S. bulbosa* Subzone, including *Geragnostus subobesus, Highgatella cordilleri, Hystricurus millardensis, Symphysurina brevispicata, Symphysurina eurekensis,* and *Symphysurina spicata* (Fig. 8).

The collection at LCM-HL437 is only 2 ft (0.6 m) above the lowest occurrence of the conodont *Iapetognathus fluctivagus* Nicholls, Miller, Nowlan, Repetski, and Ethington in collection LCM-HL435. Cooper et al. (2001) considered that the lowest occurrence of this conodont characterizes the base of the Ordovician System at the global stratotype in Newfoundland. However, their claim is disputed near the end of this report because the stratotype horizon is characterized by redeposited fossils. The olenid trilobite *Jujuyaspis borealis* Kobayashi (Plate 1, Figs. 23–27) occurs in collection LCL-HC438, one foot (0.3 m) above the base of the *S. bulbosa* Subzone, thus identifying the base of the Tremadocian Series in the Lawson Cove section. The association of the lowest occurrences of *Jujuyaspis borealis* and *Iapetognathus fluctivagus* at the base of the *S. bulbosa* Subzone is known from many locations in North America, including Texas (Miller and Stitt, 1995), the Ibex area (Miller and Taylor, 1995), the Drum Mountains (Stitt and Miller, 1987), New Mexico (Taylor and Repetski, 1995), and the southern Canadian Rocky Mountains (Westrop et al., 1981; Westrop, 1986).

Occurrences of *Jujuyaspis* and *Iapetognathus* on other continents make these genera important for worldwide correlation. *Jujuyaspis keideli* Kobayashi occurs near the base of the Tremadocian in Argentina, Bolivia, and Colombia, and this species is associated with the graptolite *Rhabdinopora flabelliformis* (Eichwald), which also has its lowest occurrence at or near the base of the Tremadocian (Aceñolaza and Aceñolaza, 1992). *Jujuyaspis keideli norvegica* Henningsmoen occurs about 3 m above the base of the Tremadocian in Norway, which is defined by the lowest occurrence of the olenid trilobite *Boeckaspis hirsuta* (Brogger) and the conodont *Iapetognathus aengensis* (Lindström) (Bruton, Koch, and Repetski, 1988). *Iapetognathus aengensis* was reported from the base of the Tremadocian in Estonia, where it is associated with graptolites of the *Rhabdinopora flabelliformis* group (Kaljo et al., 1988). *Jujuyaspis* was reported from the base of the *Yosimuraspis* Zone in South Korea (Kim and Choi, 2000). *Jujuyaspis* also occurs in China (Zhou and Zhang, 1984; Zhou et al., 1984) and in Siberia (Aceñolaza and Aceñolaza, 1992), but detailed biostratigraphic data for these occurrences is lacking. Thus a close association of the lowest occurrence of species of *Jujuyaspis* and *Iapetognathus* with the base of the Tremadocian Series exists in North America and in areas outside of North America, confirming that the base of the *Symphysurina bulbosa* Subzone and the base of the *Iapetognathus* Zone in North America correlate with the base of the traditional Tremadocian Series.

The base of the *Symphysurina woosteri* Subzone was defined in Oklahoma (Stitt, 1983) by the lowest occurrence of *Symphysurina woosteri* Walcott. At Lawson Cove the species occurs in collection LCM-HM553, 277 feet (83.9 m) above the base of the House Limestone (Fig. 8). Only three collections have been recovered from this subzone, all near its base. *Symphysurina bulbosa* and *S. eurekensis* range into this subzone from the underlying *S. bulbosa* Subzone, and together with *S. woosteri* they range upward into the overlying *Bellefontia* Zone at Lava Dam North (Table 16, Fig. 12).

BELLEFONTIA ZONE

Aitken and Norford (1967) defined the *Bellefontia-Xenostegium* Zone, and later Stitt (1983) restricted it to the interval above the *Symphysurina* Zone and below the *Paraplethopeltis* Zone in the McKenzie Hill Limestone in Oklahoma. Westrop et al. (1993) considered *Xenostegium* to be a junior subjective synonym of *Bellefontia.* This synonymy has resulted in changing the name of this zone to simply the *Bellefontia* Zone. Five collections beginning at 58 ft (17.6 m) above the base of the upper segment of the Lawson Cove section contain beautifully silicified trilobites indicative of the *Bellefontia* Zone (Fig. 8). Taxa recovered include *Bellefontia chamberlaini* Clark, *Bellefontia franklinense* (Ross), *Clelandia utahensis* Ross, *Hystricurus genalatus* Ross, *Remopleuridiella caudilimbata* Ross, *Symphysurina globocapitella* Hintze, and *Symphysurina uncaspicata* Hintze (Plate 2, Table 4). The lowest collection (LCU-HU58) may be near the base of the *Bellefontia* Zone as recognized in the Ibex area, based on its position within the *Rossodus manitouensis* Conodont Zone (Ross et al., 1997). We recovered a similar fauna at the same stratigraphic level in the Lava Dam North section and recognize that level as the base of the *Bellefontia* Zone (Fig. 12). The top of the zone is identified by a collection at 585.5 ft in the Lava Dam

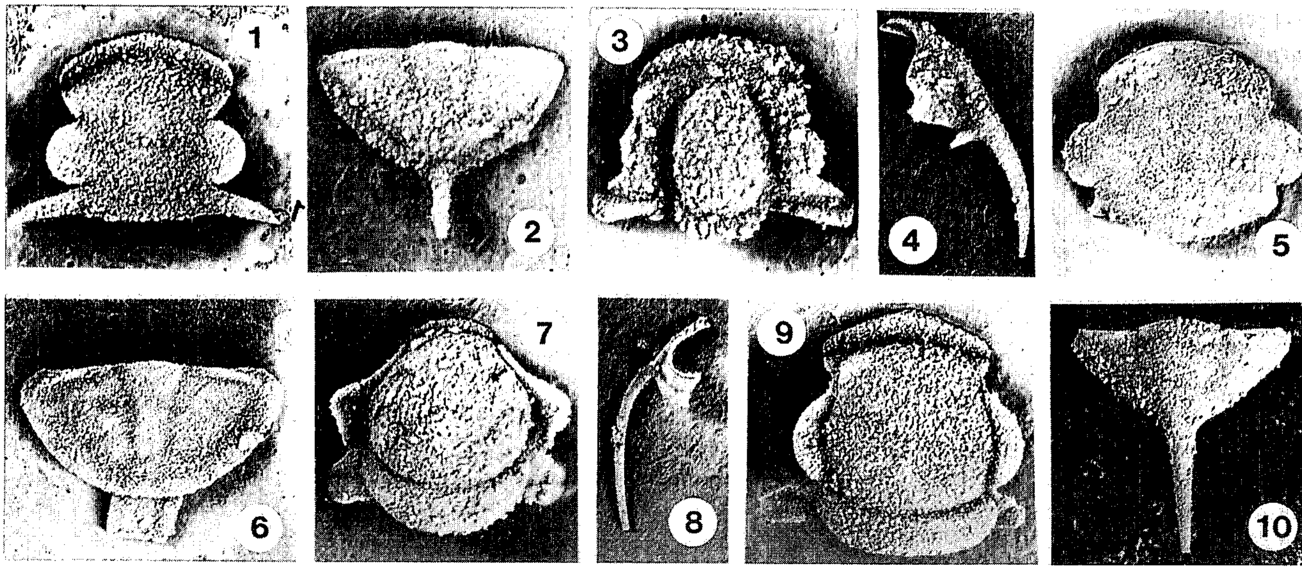


PLATE 2

Representative trilobites from the *Bellefontia* Zone, Lawson Cove section.
Occurrences are recorded in Table 6 on CD-ROM.

1, 2. *Bellefontia franklinense* (Ross). 1, cranidium, LCU-HU92, UMC 17501, x7; 2, pygidium, LCU-HU92, UMC 17502, x11.

3, 4. *Hystricurus genalatus* Ross. 3, cranidium, LCU-HU58, UMC 17503, x11; 4, librigena, LCU-HU58, UMC 17504, x7.

5, 10. *Symphysurina uncaspicata* Hintze. 5, cranidium, LCU-HU58, UMC 17505, x4.5; 10, pygidium, LCU-HU58, UMC 17506. x5.

6, *Bellefontia chamberlaini* Clark. Pygidium, LCU-HU92, UMC 17507, x3.

7, 8. *Remopleuridiella caudilimbata* Ross. 7, cranidium, LCU-HU58, UMC 17508, x10; 8, librigena, LCU-HU58; UMC 17509, x6.

9. *Praepatokephalus* sp. Cranidium, LCU-HU92, UMC 17510, x8.

North section (Table 7) that contains *Bellefontia? acuminiferentis* Ross.

Based upon his collections in the McKenzie Hill Limestone of Oklahoma, Stitt (1983) subdivided the *Bellefontia* Zone into the *Bellefontia franklinense, Bellefontia colleana,* and *Bellefontia chamberlaini* subzones. The base of each subzone is marked by the lowest occurrence of the eponymous species. Direct application of this subzonal nomenclature in the Ibex region is not possible. In the Ibex region species characteristic of the *B. franklinense* and *B. chamberlaini* subzones have been recovered. Interestingly, we recovered no species that is unique to the *B. colleana* Subzone. Further analysis and graphic correlation (Loch et al., 1999) suggests that the first appearance of *B. chamberlaini* in Utah significantly precedes its first appearance in Oklahoma. At this point we choose not to subdivide the *Bellefontia* Zone.

PARAPLETHOPELTIS ZONE

Ross (1951) established Zone C in northern Utah. Hintze (1953) applied the name *Paraplethopeltis* Zone to that interval and named *Paraplethopeltis genacurvus* Hintze and *P. genarectus* Hintze as taxa that characterize the zone.

This thin zone occurs near the top of the House Limestone at the Lava Dam North section (Table 7). The base of the zone is documented by sample LDN 586; the underlying bed contains a species assigned to the *Bellefontia* Zone. The top 9 ft (2.7 m) of the House is assigned to the overlying zone (Fig. 12).

LEIOSTEGIUM-KAINELLA ZONE

Ross (1951) established Zone D in northern Utah. Hintze (1953) named this zone based on occurrences of *Leiostegium* Raymond and *Kainella* Walcott. Ross et al. (1997) used the base of this zone as the base of the Stairsian Stage, the second stage of the Ibexian Series. Our new collections from Lava Dam North place the base of the zone at 593 ft in the measured section (Table 7, Fig. 12) based on an occurrence of *Leiostegium* sp. This collection is 9 ft (2.7 m) below the top of the House Limestone and marks the base of the Stairsian Stage in this section. *Kainella* cf. *billingsi* Walcott occurs at 599; this sample also has the highest occurrence of *Paraplethopeltis.* A more diverse fauna that includes *Leiostegium manitouensis* Walcott, *Apatokephalis finalis* (Walcott), and other trilobites referred to *Leiostegium* occur 4 ft (1.2 m) above the base of the Fillmore Formation at LDN 606 (Fig. 12). This zone continues in the Fillmore Formation at the 1965 C section. Ethington et al. (1987, Fig. 8.3) showed occurrences of taxa in this zone and Ross et al. (1997) discussed this and younger trilobite zones in the Ibex area.

ORGANOPHOSPHATIC BRACHIOPODS

L. E. Holmer, L. E. Popov, and J. F. Miller

The lingulate (organophosphatic) brachiopods from the Cambrian-Ordovician boundary beds of the Lawson Cove section are relatively small collections, most of which were picked from J. F. Miller's conodont samples following acid treatment, sieving, and heavy-liquid separation. These brachiopods were described by Popov et al. (2002). Included was one extremely abundant sample from the top of the Lava Dam North section (LDN-600). Additional collections of brachiopods from Lava Dam North and other measured sections are being studied. The materials studied represent low diversity assemblages that are dominated by a series of single acrotretide species, usually belonging to *Eurytreta.* The assemblages also include lingulide brachiopods, but they are mostly represented by juveniles. The ranges of taxa are shown on Figures 6, 8, 11, and 12; numbers of specimens are indicated in Tables 4, 5, 7, and 8.

The lowest part of the Lawson Cove section (Red Tops Member) has two species of lingulate brachiopods (Fig. 6). The lowest occurrence of *Lingulella*? *incurvata* Popov, Holmer, and Miller is in the *Eoconodontus notchpeakensis* Subzone, in sample LCL-RT28, and it occurs as high as the upper part of the *Cordylodus angulatus* Zone in the Barn Canyon Member of the House Limestone, in sample LCM-HL512 (Fig. 8). The base of the *C. minutus* Subzone (sample LCL-RT36) contains *Zhanatella utahensis* Popov, Holmer, and Miller, which occurs also near the top of the subzone. The same sample also has the lowest occurrence of a second lingulide, *Wahwahlingula* sp. This species is closely related to *Wahwahlingula antiquissima* (Jeremejew), which appears in the upper *Cordylodus proavus* Zone of northwestern Russia (Popov et al., 1989). These three distinctive lingulides occur in the same interval of strata but can be distinguished from one another rather easily. *Zhanatella utahensis* is ventribiconvex, whereas *L.*? *incurvata* and *Wahwahlingula* sp. are characterized by having elongated, dorsibiconvex shells with well developed dorsal and ventral pseudointerareas. However, the latter two differ markedly from each other in the character of postlarval surface ornament. *Lingulella*? *incurvata* has a smooth shell, whereas *Wahwahlingula* sp. possesses a fine microornament of circular pits on the postlarval shell. Some unidentified juvenile lingulide shells occur sporadically within the *Cambrooistodus minutus* Subzone. In the upper part of this subzone (samples LCL-LD46 to LCL-LD156), acrotretides are relatively more common. Mostly these specimens belong to a single species, *Quadrisonia*? *lavadamensis* Popov, Holmer, and Miller.

The lowermost *Cordylodus proavus* Zone (lower part of *H. hirsutus* Subzone) of the Lawson Cove section is very poor in brachiopods, with only scant fragments of juvenile lingulides in the lowermost part of this subzone (sample LCL-LD162.5) and *Lingulella*? *incurvata* slightly higher (sample LCL-LD164). The upper part of the *H. hirsutus* Subzone is characterized by the appearance of *Eurytreta sublata* Koneva and Popov (sample LCL-LD183), a level only 1 ft (0.3 m) above the lowest occurrence of *Cordylodus proavus* and the base of the *Missisquoia* Trilobite Zone (sample LCL-LD182). This lower level corresponds to the base of the Canadian Series. Less well preserved material assigned to this species occurs through a considerable interval of strata nearly to the top of the *Cordylodus intermedius* Zone. Outside of North America, *Eurytreta sublata* is known only from the Cambrian-Ordovician boundary beds in the Batyrbay section in the Malyi Karatau Range in Kazakhstan. There, this species appears at the 117 m level (Koneva and Popov, 1988; Holmer et al., 2001), slightly above the lowest occurrence of *Cordylodus proavus* at 109 m (Apollonov et al., 1988). These occurrences in Utah and Kazakhstan suggest that this species is quite useful for international correlation. Other components of the Lawson Cove lingulate brachiopod assemblage are transitional from underlying deposits and usually include juvenile shells of lingulides, probably *Lingulella*? *incurvata* and *Wahwahlingula* sp.

Eurytreta sublata Koneva and Popov is replaced by its descendant, *Eurytreta* cf. *bisecta* (Matthew) approximately two meters above the base of the lower subzone of the *Cordylodus lindstromi* s. l. Zone (sample LCM-HL407). This level is well below the lowermost occurrence of the conodont *Iapetognathus* and the basal Tremadocian trilobite *Jujuyaspis*. *Eurytreta* cf. *bisecta* is widespread in the Cambrian-Ordovician boundary sections of Eastern Canada, Wales, Baltoscandia, and Kazakhstan, where it is usually associated with the planktic graptolite *Rhabdinopora* (see Popov and Holmer, 1994). However, *Eurytreta* cf. *bisecta* occurs with conodonts only at Lawson Cove and in the sections of the Malyi Karatau Range in Kazakhstan. The *Eurytreta* specimens from Kazakhstan are from conodont collections made by J. F. Miller from the Batyrbay section in 1984 and 1990. These collections produced *Cordylodus lindstromi* (sensu lato; specimens may include *C. prolindstromi*) at horizons that are somewhat lower (181, 185.2, and 191 m) than *C. lindstromi* was reported previously (205 m) by Apollonov et al. (1988, Fig. 3). Miller's collections also produced *Cordylodus prion* at 185.2 m. In the Batyrbay section the lowest occurrence of *Eurytreta* cf. *bisecta* is at the 185.2 m level (Abdullin and Chakabaev, 1984, Fig. B11), and it ranges farther up in the *Cordylodus lindstromi* Zone. These occurrences of *Cordylodus* species indicate that the lowest occurrence of *Eurytreta* cf. *bisecta* is at a similar homotaxial position at Batyrbay and Lawson Cove. At both sections it is possible to document occurrences of this species somewhat below the base of the traditional Tremadocian Series.

In the Lawson Cove section the lower part of the *Cordylodus lindstromi* sensu lato Zone also contains the lowest occurrence of the siphonotretide *Schizambon typicalis* Walcott (sample LCM-HL421). *Eurytreta* cf. *minor* Biernat appears somewhat above the base of the *Cordylodus angulatus* Zone (sample LCM-HL462), replacing its ancestor, *Eurytreta* cf. *bisecta*.

Conotreta millardensis Popov, Holmer, and Miller is the oldest lingulate that is restricted to Tremadocian strata at Lawson Cove. It is found in the upper part of the *Cordylodus angulatus* Zone in a single sample (LCM-HL498) and occurs with the conodont *Iapetognathus sprakersi*. The uppermost part of the Lawson Cove section contains only rare fragmentary specimens and juvenile lingulides.

Preliminary study shows that a new fauna of organophosphatic brachiopods occurs in the lowermost part of the Fillmore Formation. Sample LDN-606, from only 4 ft (1.2 m) above the base of the Fillmore, contains several different lingulides, including *Spinilingula* n. sp. and the acrotretoid *Ottenbyella* n. sp. (Fig. 12) This fauna occurs slightly below the top of the *Rossodus manitouensis* Conodont Zone and within the lower part of the *Leiostegium-Kainella* Trilobite Zone. This new fauna also occurs in the southern extension of the 1965 C section (see description in Appendix) at 14.5 ft in the measured section, which is 6 inches (15 cm) above the base of the Fillmore Formation and within the same biozonal units as the other occurrence. *Spinilingula* Cooper and *Ottenbyella* Popov and Holmer have been found as high as 21 ft (6.4 m) above the base of the 1965 C section, also in the lower Fillmore Formation (Fig. 11). Occurring with them is *Eurytreta* sp. aff. *chabakovi* (Lermontova). *Ottenbyella* is known from the Ceratopyge Limestone on the island of Öland, Sweden and from the Malyi Karatau, Kazakhstan. *Eurytreta chabakovi* occurs in the uppermost Tremadocian in Baltoscandia.

In general, the observed faunal changes in the lingulate brachiopod faunas near the Cambrian-Ordovician boundary in the Lawson Cove section are very similar to the pattern of faunal changes reported previously for the East Baltic and Kazakhstan (Popov and Holmer, 1994; Koneva and Popov, 1983, 1988). In all areas the diversity of the lingulate brachiopods also decreases significantly below the base of the *Eoconodontus* Zone. Younger strata include usually one or two acrotretide species (usually *Eurytreta*) in association with juvenile lingulides. The most significant difference between the brachiopod assemblages from the Lawson Cove section and those from the East Baltic and Kazakhstan is the near absence of *Broeggeria* Walcott, which is a very characteristic and widespread genus in the Cambrian-Ordovician boundary interval of other parts of the world (Popov and Holmer, 1994). In addition, faunas from western North America contain no acrotretides of the families Scapheasmatidae and Eoconulidae, nor the lingulid genus *Mirilingula* Popov, although these taxa are rather common in coeval strata in Kazakhstan (Holmer and Popov, 1994; Koneva and Popov, 1983, 1988). Lingulate brachiopod faunas experienced an apparent decrease in diversity in the Cambrian-Ordovician boundary interval. The recovery in diversity of these faunas apparently did not take place until the mid Tremadocian *Paltodus deltifer* Conodont Zone, when typical Ordovician lingulide and acrotretide taxa appeared in abundance in Baltoscandia.

Despite some differences in the lingulate brachiopods at Lawson Cove compared with other parts of the world, there are significant similarities. The occurrence of the same taxa at Lawson Cove and Lava Dam North and in other parts of the world and also the overall pattern of faunal changes demonstrate that these brachiopod faunas, especially the acrotretides, have considerable potential for international correlation.

CALCITIC BRACHIOPODS

J. H. Stitt and J. F. Miller

Brachiopods are not abundant in the Lawson Cove section, with only 62 valves recovered from 10 collections

(Tables 4, 5; Figs. 6, 8). They are generally not abundant in the Lava Dam Member of the Notch Peak Formation (Hintze et al., 1988) or in the House Limestone (Jensen, 1967) in the Ibex area. A useful brachiopod biostratigraphy was established in Oklahoma and Texas, where brachiopods are more abundant and diverse in the interval from the *Saukiella serotina* Subzone of the *Saukia* Zone through the *Bellefontia* Zone (Freeman and Stitt, 1996).

In Oklahoma, species of *Finkelnburgia* Walcott occur in the *Saukiella serotina* Subzone and are succeeded up section by *Nanorthis hamburgensis* (Walcott). The lowest occurrence of the latter species is at the base of the *Eurekia apopsis* Zone, and it ranges upward through the overlying *Missisquoia* Zone and into the upper part of the *Symphysurina brevispicata* Subzone (Freeman and Stitt, 1996). *Apheoorthis ornata* Ulrich and Cooper and *Apheoorthis oklahomensis* Ulrich and Cooper have their lowest occurrence at the base of the *Missisquoia typicalis* Subzone of the *Missisquoia* Zone, and they range through the *Symphysurina brevispicata* Subzone to the top of the overlying *Symphysurina bulbosa* Subzone. The same succession is present in Texas (Winston and Nicholls, 1967; see revisions in Miller et al., 1982), with *N. hamburgensis* and species of *Apheoorthis* ranging only into the base of the *S. bulbosa* Subzone. This sequence of brachiopod genera, with some different species, is present at Mt. Wilson in the southern Canadian Rocky Mountains (Loch et al., 1993).

Some of this brachiopod biostratigraphy can be pieced together in western Utah by combining the brachiopod occurrences from other sections in the Ibex area with those from Lawson Cove. Hintze et al. (1988, Table 4) reported *Billingsella* from the upper part of the Red Tops Member at Steamboat Pass. The occurrence is from the *Eoconodontus notchpeakensis* Subzone and from the *Saukiella junia* Subzone. No identified specimens of *Finkelnburgia* were reported from the *Saukiella serotina* Subzone by Hintze et al. (1988), and there are no published reports of *Nanorthis hamburgensis* from the *E. apopsis* Zone. None of these taxa occurs in the Lawson Cove section.

At the Lava Dam Five section, unit 61 contains many brachiopods, including abundant *Glyptotrophia imbricata* Ulrich and Cooper and *Nanorthis hamburgensis*, rare *Syntrophina campbelli* (Whitfield), and the trilobite *Missisquoia typicalis*. This occurrence is 3.5 ft (1.1 m) above the base of the *M. typicalis* Subzone and only slightly above the Lawson Cove Bed. Jensen (1967) reported *N. hamburgensis* from much higher in the section, ranging from the top of the House Limestone through the lower half of the overlying Fillmore Limestone.

In the lower Lawson Cove section, *Apheoorthis ornata* and *Apheoorthis oklahomensis* have their lowest occurrences at the base of the *Missisquoia typicalis* Subzone in sample LCL-LD192 (Table 2), slightly below the Lawson Cove Bed. *Apheoorthis oklahomensis* also occurs abundantly just 4 ft (1.2 m) higher (sample LCL-LD196), slightly above the Lawson Cove Bed, in unit 30 of the described section. This occurrence is in the same stratigraphic position as the brachiopod collection from Lava Dam Five noted above, but the only taxon in common is the trilobite *M. typicalis*. At Lawson Cove the two species of *Apheoorthis* range upward into the upper part of the *Symphysurina brevispicata* Subzone (Fig. 8). *Apheoorthis* cf. *A. melita* (Hall and Whitfield) occurs in two collections in the House Limestone, one (sample LCM-HL437) at the base of the *Symphysurina bulbosa* Subzone, and the other (LCM-HL535) near the top of the subzone. Jensen (1967) reported that *Apheoorthis* cf. *A. melita* was scarce but ranged as high as 170 feet (51.5 m) above the base of the House in the Ibex area. Jensen reported no additional brachiopods from the middle and upper parts of the House Limestone that are exposed in the Lawson Cove section.

Ethington et al. (1987, Fig. 8.3) reported several brachiopods from the uppermost House Limestone and lowermost Fillmore Formation in a section located between the Lava Dam North and 1965 C sections. They reported *Nanorthis multicostata* from the upper House Limestone in the upper ca. 15 ft (4.6 m) of Zone B (*Bellefontia* Zone of this report) and into the lower ca. 4 ft (1.2 m) of Zone C (*Paraplethopeltis* Zone). The upper 2 ft (0.6 m) of the *Bellefontia* Zone and the lower 4 ft of the *Paraplethopeltis* Zone contain *Syntrophina campbelli*. Jensen (1967) considered this species to be diagnostic of his *Syntrophina* Brachiopod Zone in the upper 10 ft (3.0 m) ledge of the House Limestone. As noted above, *Syntrophina campbelli* occurs rarely near the base of the *Missisquoia typicalis* Subzone at Lava Dam Five. Both of these occurrences are in very shallow lithofacies near the boundaries of different third-order sequences (see section on Sequence Stratigraphy), and both occurrences include *Nanorthis hamburgensis*.

It appears that some of these brachiopods are useful for correlation. However, the extended ranges and repeated occurrences at similar levels in different sequences suggest that some taxa, e.g., *Nanorthis hamburgensis* and *Syntrophina campbelli*, occur in similar facies at quite different times.

SEQUENCE STRATIGRAPHY

J. F. Miller and K. R. Evans

We recognize fourteen depositional sequences in Utah in the upper part of the Orr Formation, the Notch Peak Formation, the House Limestone, and the lowermost beds of the Fillmore Formation (Figures 2 and 3). The lower twelve of these sequences are also present in central Texas, but the youngest two are not exposed (Fig. 14).

BACKGROUND

The western passive continental margin of Laurentia formed during a Late Proterozoic rifting event (Stewart, 1976), and lower Paleozoic strata of the eastern Great Basin were deposited on a tropical carbonate platform that subsided rapidly after rifting. This subsidence produced accommodation for deposition of ca. 10,000 ft (3050 m) of Cambrian and ca. 5000 ft (1525 m) of Ordovician strata. Thus, Cambrian-Ordovician strata are an essentially continuous record of marine sedimentation broken only briefly by a few episodes of sea-level fall that are of sufficient magnitude to produce minor karst surfaces or erosional truncations. These karst and erosional surfaces and lithofacies shifts form natural boundaries between stratigraphic sequences. Strata also record a number of lithofacies shifts that reflect the interplay between sea level changes and dynamic sedimentation.

Cambrian and lower Ordovician formations are part of the Sauk Sequence of Sloss (1963), which Palmer (1981) divided into three parts, Sauk I to III. Golonka and Kiessling (2002) recognized an additional part, Sauk IV, which they split off from the upper part of Palmer's Sauk III. Sauk IV begins at the upper Tremadocian unconformity, which we consider to correlate approximately with the boundary separating the *Rossodus manitouensis* Zone from the Low Diversity Interval. We recognize a major sequence boundary at essentially this level, between Sequences 13 and 14, and we place the base of Sauk IV at this sequence boundary. This horizon is 10.5 ft (3.2 m) above the base of the Fillmore Formation at the 1965 C section. Thus, Sauk III includes the upper part of the Orr Formation, the Notch Peak and House formations, and the basal beds of the Fillmore Formation. Sauk IV includes most of the Fillmore Formation and younger strata to the top of the Sauk Sequence (top of Eureka Quartzite). Herein, we consider the entire Sauk III interval.

Palmer (1981) placed the base of the Sauk III interval at the base of the *Elvinia* Trilobite Zone, at the base of the Corset Spring Shale Member of the Orr Formation in the central House Range. Due to facies changes, this boundary is within the Steamboat Pass Shale Member in the southern House Range and in the Wah Wah Mountains. We interpret these strata as a lowstand deposit, within which Evans (1997) identified a karst surface slightly above the base of the *Elvinia* Zone; we interpret this karst surface as the Sauk II-Sauk III boundary. This interval is dominantly shaly, but there is a shift to relatively pure carbonates in the Sneakover Member near the top of the Orr Formation. This carbonate succession continues through the Notch Peak and House formations. Overlying strata of the Fillmore Formation record a return to mixed shale and carbonate, and our study interval extends into the lowest part of these beds.

In Texas the Sauk II-Sauk III boundary is also an unconformity within lowstand deposits. The Lion Mountain Sandstone Member of the Riley Formation is a regressive unit that is unconformably overlain by the transgressive Welge Sandstone Member of the Wilberns Formation (Fig. 14), which is assigned to the *Elvinia* Zone (Barnes and Bell, 1977). The sand-on-sand unconformity at the formation boundary correlates with the karst surface discussed above.

Division of the Sauk III interval into smaller sequences began during the 1980's. Early research was near the Cambrian-Ordovician boundary and included reports by Miller (1984, 1992) in the USA, Erdtmann (1986) in Norway, and Nicoll et al. (1992) in Australia and Norway. Miller (1995) studied strata in Utah and Texas and recognized several named sea-level "events" that had been proposed in the earlier reports, as well as several additional sea-level fluctuations. These event horizons constitute many of the sequence boundaries discussed herein.

Osleger and Read (1993) proposed a sea-level curve for Upper Cambrian strata in several parts of the United States, including the House Range, and they identified several third-order sequences. Because their sequence interpretations are based on Fisher Plots and they did not report their sequence boundaries in measured sections, we can not correlate our interpretations precisely with theirs. We consider only their two youngest Late Cambrian sequences (Fig. 15), and it appears that the lower of these third-order sequences can be divided into our Sequences 1 and 2, and their highest sequence can be divided into our Sequences 3 to 7.

Ross and Ross (1995) proposed a sea-level curve for Ordovician strata and recognized a series of third-order sequences. We reconsider their two lower sequences (Fig. 15). We divide their lowest Ordovician sequence into our Sequences 8 and 9, and we divide their second sequence into our Sequences 10 to 13. The base of their next third-order sequence nearly coincides with our Sequence 14, which we discuss briefly.

SEQUENCE STRATIGRAPHIC TERMINOLOGY

The terminology of sequence stratigraphy usually includes sequences, various types of sequence boundaries, parasequences, systems tracts, and features such as maximum flooding surfaces or zones. Much of the terminology is based on models of sequence stratigraphy developed for siliciclastic sediments, and various models define the same terms differently. Previously proposed sequence models may not apply to the thick carbonate succession deposited on the Utah miogeocline. For example, we are unable to recognize maximum flooding surfaces because, despite the rapid rate at which accommodation was produced, carbonate productivity essentially kept pace with accommodation. We do not use the term "parasequences" because the term has been defined in different ways within different sequence models. We do not employ systems-tract terminology, although we recognize strata that were deposited during lowstands and highstands of sea level.

We use generic stratigraphic terminology that includes an informal hierarchy of sequences, divisions of sequences referred to as packages, and even thinner intervals. We recognize sequence boundaries and sequence-boundary zones and surfaces of unconformity or intervals of strata that can be correlated with unconformity surfaces elsewhere. Transgressive and regressive events and some highstands and lowstands are also named herein.

Sequences are generally understood to be unconformity-bounded intervals of strata and laterally equivalent intervals of strata that record continuous deposition. Instead of "parasequences" or "parasequence sets" we employ the generic term "packages" for intervals of strata that appear to have been deposited conformably and in grossly similar settings. Associations of lithofacies and their superpositional succession constitute much of the evidence for identifying the stratigraphic packages recognized herein. Some of our sequences or packages display very thin divisions that we refer to simply as "meter-scale cycles."

Sequence boundaries, as we use the term herein, are based on the occurrence of karst or microkarst surfaces, planar truncation surfaces in subtidal carbonate lithofacies, or large increases in the quartz sand content of insoluble residues that are associated with increases in depositional energy. Some sequence boundaries are placed at stratigraphic levels that record increases in depositional energy without higher quartz content but where laterally equivalent strata record hiatus. With each type of evidence, we attempt to correlate surfaces of erosion with coeval strata that have missing faunal zones, subzones, or physical expressions of hiatus (karst, microkarst, or planar truncation surfaces). Some sequence boundaries comprise a thin interval of strata, referred to as a "sequence boundary zone," that have two karst or truncation surfaces that are closely spaced, within ca. one meter.

Sequence boundaries and their correlative conformities may form as a response to local conditions of accommodation and sedimentation rates and may not necessarily form as a response to eustatic fall or stillstand. Where we can identify a widespread surface of erosion in shallow-water carbonates, we interpret this surface as recording a relative sea-level fall. In contrast, marine flooding surfaces may result from relative sea-level rise, from subsidence, from decreases in the rate of sedimentation, or from a combination of these processes. However, some of the sequence boundaries and flooding surfaces that we recognize occur in several different depositional settings in widely separated areas, making it more likely that such

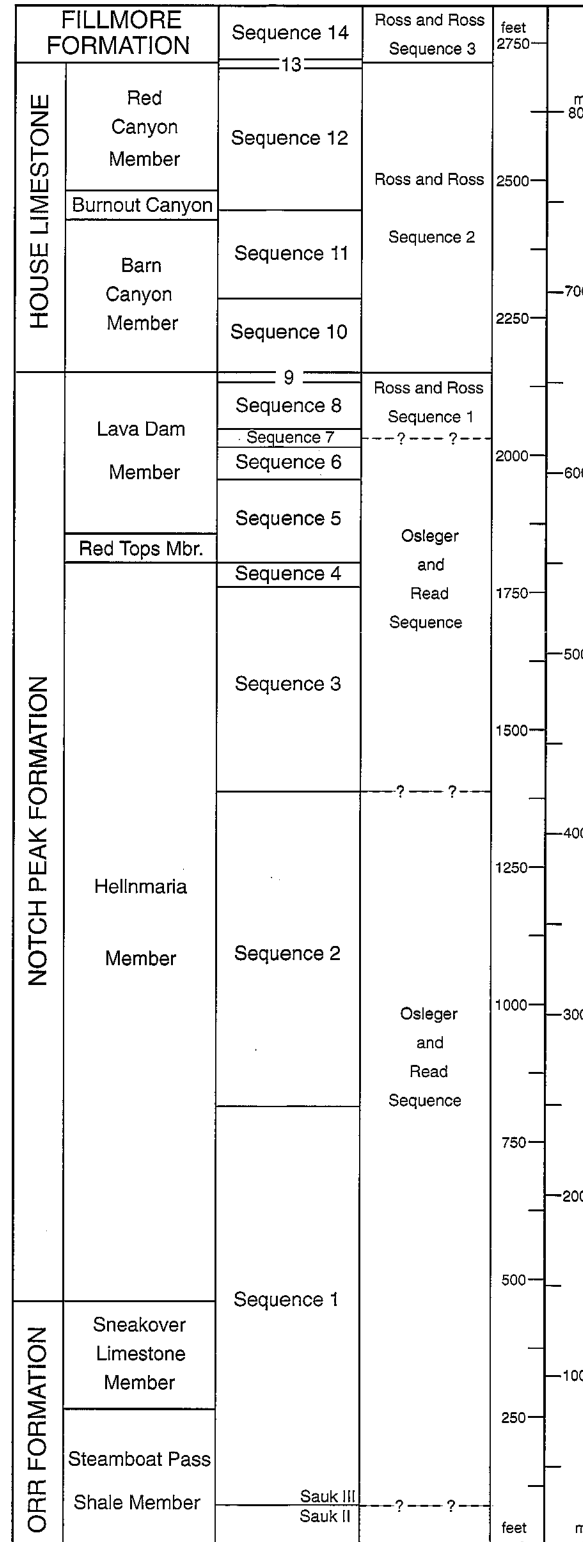


Figure 15. Utah lithostratigraphic and sequence stratigraphic units recognized in this report compared with third-order sequences recognized by Osleger and Read (1993) and Ross and Ross (1995).

sequence boundaries and flooding surfaces developed in response to eustatic changes rather than in response to local conditions.

Transgressions and regressions or transgressive and regressive intervals are related to relative positions of shorelines. We have followed the terminology of other authors by recognizing named features, including Lange Ranch Eustatic Event (renamed herein as Lange Ranch Lowstand) and Black Mountain Eustatic Event of Miller (1984), *Acerocare* Regressive Event, *Peltocare* Regressive Event, and *Ceratopyge* Regressive Event of Erdtmann (1986). We interpret these features as being related to intervals of relative sea-level fall. We recognize the Stonehenge Transgression (Taylor et al., 1992) as being related to a prolonged interval of relative sea-level rise. We introduce a new name, the Sauk III Transgression, for the profound sea-level rise that began during *Elvinia* Zone time (see Palmer, 1981).

The terms lowstand strata, lowstand, and named lowstands such as the Red Tops Lowstand, are interpreted to have formed during a prolonged period of low sea level following a relative sea level drop. Lowstand strata have these characteristic features: 1) thin, fine-grained siliciclastic strata; 2) carbonate strata with pink to red to rusty-brown color; 3) intervals of laterally continuous high-energy lithologies, including ooid, peloid, oncoid, and trilobite grainstones, laminated to cross-laminated fine grainstone, and flat-pebble conglomerate; 4) thin stromatolite or thrombolite beds; 5) chert-clast conglomerate; 6) carbonate strata with high concentrations of fine quartz sand in insoluble residues; 7) white to brown chert that locally is up to 50% of cherty carbonate strata; 8) paleokarst features; 9) glauconite in carbonates; and 10) thick intervals of zebra-rock dolomite. Lowstand strata are of different thicknesses in different sequences, and such strata may vary significantly along strike. None of the lowstand intervals that we recognize contains all ten of the features listed above. Lowstand strata tend to weather recessively in outcrop, such as strata of the Corset Spring and Red Tops lowstands, or they may form major cliffs, such the sandy and chert-rich Burnout Canyon Lowstand.

Lowstand strata may comprise parts or all of some sequences or packages. Lowstand strata may or may not be bounded by truncation surfaces that are interpreted as boundaries between sequences or smaller packages, but many sequence boundaries recognized herein occur at the bases of lowstand intervals.

Comparable to our use of the term "lowstand," the term "highstand" here refers to a long-term state of relatively high sea level rather than linkage with existing systems tract models. By introducing names for lowstands and highstands, we present these interpretive features as a means for correlating strata that are constrained by a biostratigraphic framework. Introduction of these terms becomes a means for testing interpretations of relative sea level fluctuations in other regions against the remarkably thick and relatively complete stratigraphic record in the Ibex area.

Detailed biostratigraphic correlation allows us to recognize some sequences in other areas, although detailed correlations to most areas are beyond the scope of this report. In some areas we can identify missing biozonal units or identify erosion surfaces that correlate to conformable intervals in coeval Ibex sequences. As an example of their widespread character, Ibex sequences and package boundaries are compared with coeval sequences and boundaries in the Threadgill Creek and Lange Ranch sections in central Texas, and selected boundaries or intervals are correlated to Colorado, Oklahoma, and North China. Texas strata were deposited on a cratonic carbonate platform that experienced much slower rates of subsidence than the Utah miogeocline, resulting in a thinner stratigraphic succession. Texas strata thus form a strong contrast with the Ibex succession. Sequences and sequence boundaries recognized in Utah are recognizable in Texas but are expressed quite differently. For example, many lowstand intervals in Utah are recorded as unconformity or truncation surfaces in Texas.

INSOLUBLE RESIDUES

Part of our interest in the sequence stratigraphy of these strata is an outgrowth of research on their conodont biostratigraphy. Hundreds of carbonate samples (mostly limestone) were dissolved in order to obtain conodonts for biostratigraphic control. Samples from several sections were processed so that data on the insoluble residues was also obtained, following procedures discussed by Miller (1995, 2003). Examination of these residues shows that a few contain significant amounts of iron-rich or silicified ooids, euhedral quartz crystals, or silicified trilobite skeletal debris. However, most of the insoluble material is fine detrital quartz sand.

Tables 10–20 (CD-ROM) record insoluble residues of samples processed from all or part of these sections: East Shoreline Butte, Notch Peak, Sneakover Pass, the three segments of the Lawson Cove section, Lava Dam North, 1965 C Section, Sevier Lake Corral, Tank Canyon, and Section A. Table 21 records insoluble residues from part of the Lange Ranch section in Texas. The total amount of rock processed is shown for each sample. There are some differences between sample data from tables showing fossil occurrences compared with insoluble residue data from the same samples. For example, some samples at the upper segment of the Lawson Cove section were processed directly with hydrochloric acid so as to obtain insoluble residue data (Table 15), and there are no conodonts from these samples in the corresponding conodont data table (Table 6). Insoluble residue data are shown graphically on Figures 16 and 17.

Per mil concentrations of insoluble residue show clearly cyclic patterns of variation. High concentrations of insoluble residue gradually diminish to lower values in successive samples, followed by abrupt increases to high levels. These cyclic repetitions are one criterion for recognizing depositional packages and some sequence boundaries. Miller (1995) used a smaller set of insoluble residue data from the Lawson Cove and Lange Ranch sections to identify eustatic "events," and these data are incorporated into the larger data set of this report.

The quartz sand found in the insoluble residues of limestone samples is interpreted to been eroded from somewhat distant landmasses, transported, and deposited in the Ibex area. Two known source areas are the Transcontinental Arch and the Tooele-Uintah Arch. The Transcontinental Arch was a large topographic high that was far east of the Ibex area. Other topographic highs may have existed east or north of the Ibex area, such as the Salmon River Arch (Rowell and Rees, 1981). A southern source in the Wah Wah Arch is also possible. Drops in sea level exposed these landmasses to subaerial erosion, and siliciclastic material prograded into the Ibex area. Conversely, transgression covered these siliciclastic source areas and reduced the influx of quartz sand. Repeated fluctuations in the concentration of this quartz sand are interpreted as tracking repeated relative sea-level changes.

Based on the above model, it appears that regressions and transgressions were of unequal duration. Increases in siliciclastic content are abrupt, whereas decreases are gradual, and these changes imply that regressions were abrupt and transgressions occurred slowly. Boundaries between packages of strata recognized herein generally are placed at the marked increases in siliciclastics because they are more distinctive than the gradual decreases. Increases in siliciclastic content are used in conjunction with other criteria listed above in order to recognize lowstand strata.

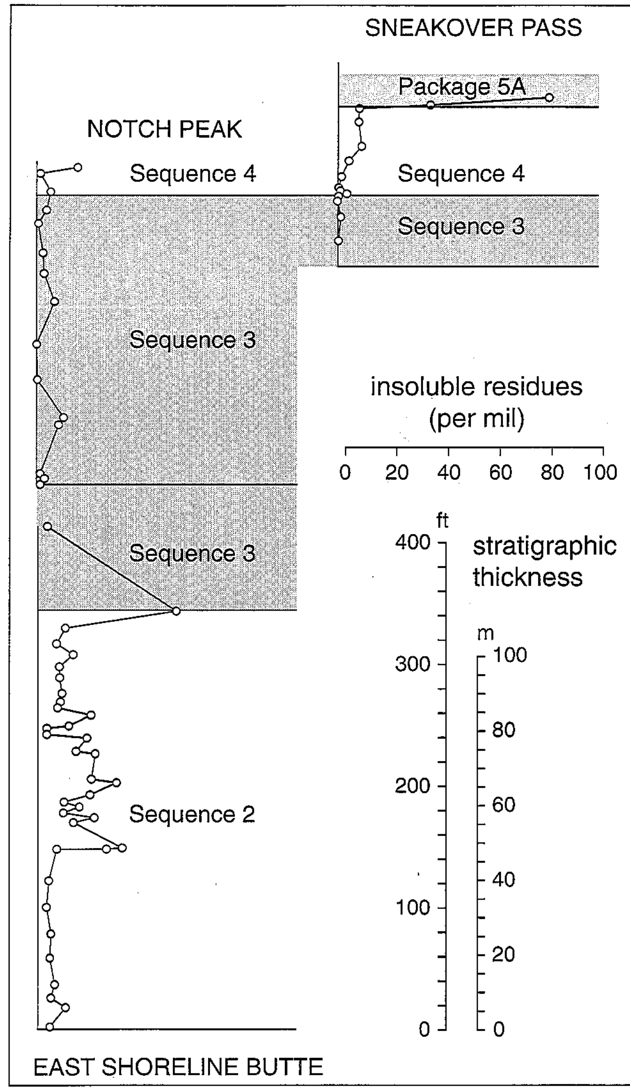


Figure 16. Curves for East Shoreline Butte and lower parts of Notch Peak and Sneakover Pass sections showing variation in concentration of light fraction (specific gravity < ca. 2.87) of insoluble residues of conodont samples; material is mostly fine quartz sand. Odd-numbered sequences are shaded. Horizontal and vertical scales are uniform for all sections. Sequences 2–4 are part of Hellnmaria Member; Sequence 5 is base of Red Tops Member. Compare with similar insoluble residue curves shown on Figures 14 and 17. For original data, see Tables 10–12 on CD-ROM.

INTERVALS OF LOWSTAND STRATA

We recognize eight major, conspicuous lowstand intervals, which are shown as shaded intervals on Figures 2 and 3. Thinner, less conspicuous lowstand strata (1.5 to 7 m thick) occur at some other sequence and package boundaries, such as at the base of Sequence 6 (Package 6A). The Corset Spring Lowstand is at the base of the interval we studied; it is within the Steamboat Pass Member of the Orr Formation in the southern House Range and northern Wah Wah Mountains and in the Corset Spring Member of the Orr Formation in the Orr Ridge area of the central House Range. Above the sequence boundary that marks the base of the Sauk III interval, the Corset Spring Lowstand is 137 ft (41.8 m) thick in the northern Wah Wah Mountains. The Red Tops Lowstand is 52 ft (15.8 m) thick; it coincides with the Red Tops Member and includes the boundary between Sequences 4 and 5. (Thicknesses for

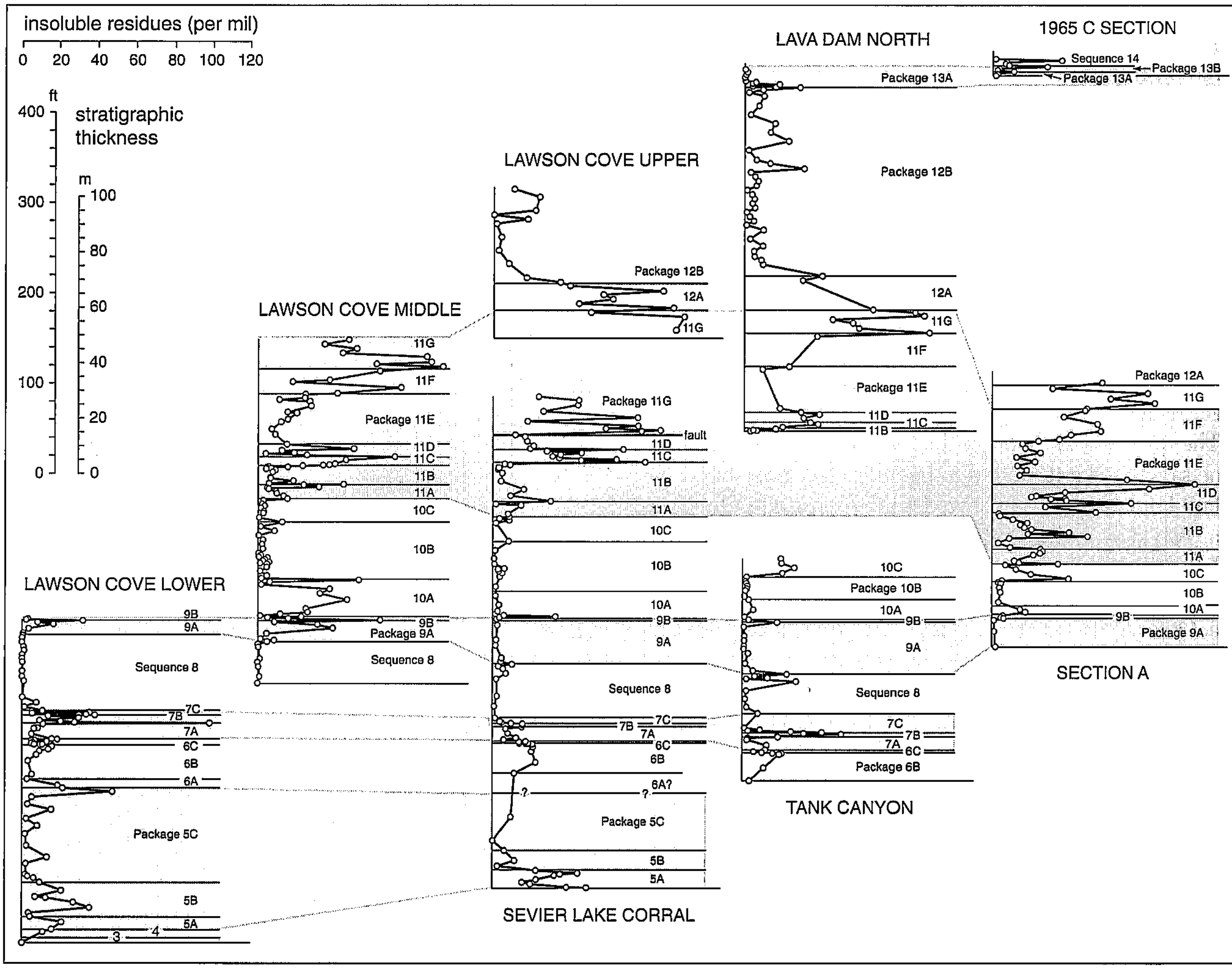


Figure 17. Insoluble residue curves for Lawson Cove, Sevier Lake Corral, Tank Canyon, Lava Dam North, 1965 C section, and Section A. Curves show variation in concentration of light fraction (specific gravity < ca. 2.87) of insoluble residues of conodont samples; material is mostly fine quartz sand. Odd-numbered sequences are shaded. Horizontal and vertical scales are uniform for all sections. For original data, see Tables 13–20 on CD-ROM.

the Red Tops and most younger lowstand intervals are reported for the Lawson Cove section and are shown on Figure 3; the youngest lowstand is based on the Lava Dam North and 1965 C sections.) The Lange Ranch Lowstand (formerly referred to as the Lange Ranch Eustatic Event by Miller, 1984, 1992 and other authors) is 38 ft (11.6 m) thick and coincides with Sequence 7. The Basal House Lowstand includes the lower 42 ft (12.8 m) of the House Limestone and includes Package 10A. The Drum Mountains Lowstand is 16 ft (4.9 m) thick and includes Package 11A and the lower part of 11B. The Burnout Canyon Lowstand is 53 ft (16.2 m) thick and coincides with the Burnout Canyon Member. The Tule Valley Lowstand spans the House-Fillmore contact and includes Sequence 13 and part of Sequence 14.

The thickness of strata between lowstands (excluding the Corset Spring Lowstand) is fairly uniform (Fig. 3). If one assumes that this uniform thickness of strata may be more or less proportional to time, it appears that the cyclicity of sea-level changes was somewhat regular.

In summary, shifts from lowstand to transgressive portions of sequences are sharp in some sequences and transitional in others. Changes from transgressive to highstand components of these sequences are mostly transitional and not clearly delineated. Generally, we are unable to recognize such features as maximum flooding surfaces, probably because we are dealing with "keep-up" carbonate deposition during periods of rapid sea-level rise (Sarg, 1988). The Sneakover Limestone and lower Hellnmaria members constitute a major relative sea-level rise that we refer to as the Sauk III Transgression. Highstand carbonates comprise the middle and upper parts of the Hellnmaria Member, and we refer to these strata as the Hellnmaria Highstand (Fig. 2).

LOWER TO MIDDLE MILLARDAN SEQUENCES

We recognize four sequences that comprise the upper part of the Orr Formation and the Hellnmaria Member of the Notch Peak Formation. The base of Sequence 1 is well documented. Sequence 1 includes basal lowstand deposits associated with the Sauk II–III boundary (Corset Spring Lowstand), followed by the Sauk III Transgression, and ending with the Hellnmaria Highstand. Sequences 2 and 3 are less well documented than younger sequences, but we include them for completeness and so that others can test these ideas. The boundaries of Sequence 4 at the top of the Hellnmaria are more clearly delineated than boundaries between Sequences 1–3. Sequence 4 is transitional to the Red Tops Lowstand in Sequence 5. Sequences 1–4 form a natural unit of mostly clean carbonates between the Corset Spring and Red Tops lowstands.

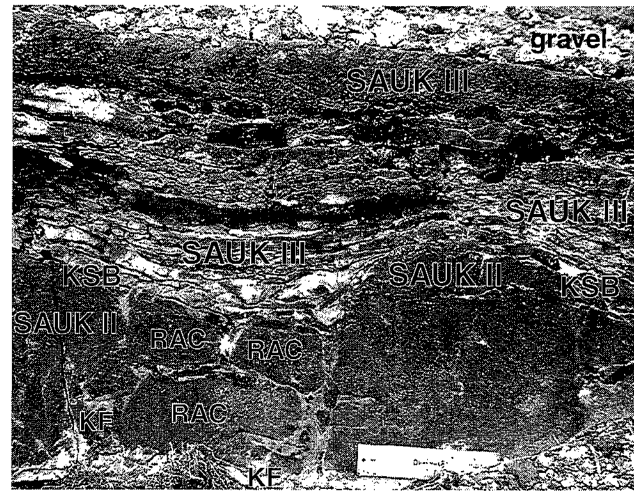


Figure 18. Karst sequence boundary (KSB) between Sauk II and Sauk III large sequences in Lawson Cove Reservoir section of Hintze and Palmer (1976, Fig. 5) and Evans (1997). Strata are near middle of Steamboat Pass Shale Member of Orr Formation. KF = karst filling, material of the Sauk III transgression that fell into solutionally enlarged joints which formed during earlier subaerial exposure. RAC = rounded autoclasts formed by dissolution during subaerial exposure. Ruler near bottom is ca. 6 inches (15 cm) long.

SEQUENCE 1

The base of Sequence 1 is near the base of the Corset Spring Shale Member of the Orr Formation in the central House Range and within the Steamboat Pass Shale Member of the Orr Formation in the Steamboat Pass-Lawson Cove area (Fig. 2). We identify the Corset Spring Shale and upper part of the Steamboat Pass Shale as lowstand strata, based on a study by Evans (1997). He identified a karst horizon 85 ft (25.9 m) below the top of the Steamboat Pass Shale Member at Lawson Cove and about 90 ft (27.4 m) below the top of the Corset Spring in the Orr Ridge area of the central House Range. Evans (1997) interpreted this karst horizon (Fig. 18) as a subaerial exposure surface and identified this horizon as the most regressive part of the lowstand. This karst horizon is the base of our Sequence 1. It is within an interval of strata that we refer to as the Corset Spring Lowstand on Figure 2. This karst horizon is ca. 20 ft (6.1 m) above the lowest occurrence of the *Linnarssonella girtyi*, at the base of the *Linnarssonella* Brachiopod Zone. The base of this zone is essentially coincident with the base of the *Elvinia* Trilobite Zone (Kurtz, 1971), so the karst horizon is within the lower part of the *Elvinia* Zone. Hintze and Palmer (1976, Fig. 3, p. G20) reported *Dunderbergia* Zone trilobites at a level somewhat below this karst horizon and reported *Elvinia* Zone trilobites somewhat above this level in the Lawson Cove area. Hintze and Palmer (1976, Fig. 2) identified *Elvinia* Zone trilobites in the uppermost bed of the Johns Wash in the southern Snake Range, Nevada. This level crops out just below the Corset Springs Shale on Orr Ridge in the Central House Range. Palmer (1981) located the Sauk II-Sauk III boundary at the base of the *Elvinia* Zone, but more detailed study results in moving the boundary slightly above the base of that zone, to the karst horizon noted above.

Sequence 1 thus extends through younger strata of the Pterocephaliid Biomere and into the lower part of the Ptychaspid Biomere; the boundary between these biomeres is a little above the middle of the Sneakover Limestone Member of the Orr Formation and near the middle of Sequence 1. Trilobites of the *Taenicephalus* Zone are reported from Sequence 1 in the Sneakover Member at Lawson Cove (Hintze and Palmer, 1976, Fig. 3, p. G19) and in the lower Hellnmaria Member at Sneakover Pass (Hintze et al., 1988, p. 16). The stratigraphic position of the top of that zone relative to the top of Sequence 1 is unknown in Utah. There is no conodont biozonation established in Hellnmaria or older strata that are assigned to this sequence.

The top of Sequence 1 is at the top of the Lower Map Unit of the Hellnmaria Member in the Steamboat Pass area. This interval is mostly unfossiliferous and has been described as the top of the "lower limestone part" of the

Hellnmaria Member in the Lawson Cove area (see Hintze et al., 1988, Fig. 3). These strata include the lower 374 ft (114.0 m) of the Hellnmaria at Steamboat Pass and the lower 440 ft (134.1 m) of the Hellnmaria at Lawson Cove. The interval is a succession of meter-scale cycles of lime mudstone in the upper part of Sequence 1. The entire thickness of Sequence 1 in the Lawson Cove area is 720 ft (219.5 m); see Table 22. We have not studied most of the type section of the Hellnmaria Member at Sneakover Pass, so we do not attempt to locate the top of Sequence 1 in that area. Sequence 1 at the East Shoreline Butte section includes the top beds of the Sneakover Member of the Orr Formation and lower Hellnmaria strata that are thin-bedded to laminated, deep subtidal lime mudstones. However, we can not recognize the top of Sequence 1 in this deep-water setting.

The base of Sequence 2 in the Lawson Cove area is an interval of zebra-rock dolomite. No such lithology is known in the East Shoreline Butte area, and there is no definite evidence of lowstand strata there in the lower to middle Hellnmaria. However, there is a thick covered interval in this section (unit 15 in section description of East Shoreline Butte) that probably is either fault controlled or conceals non-resistant lithology, or both (Fig. 19). Strata of described unit 14 are very argillaceous, and this covered interval may conceal silty or shaly strata deposited during the lowstand or stillstand immediately above Sequence 1. In this scenario, the middle white band on the west face of Notch Peak Mountain (Fig. 20) is the equivalent of these shaly lowstand deposits at East Shoreline Butte, above Sequence 1. Such an explanation is speculative, however, and we are unable to recognize with certainty the top of Sequence 1 in Tule Valley sections. This sequence includes strata of the Orr Formation, which have an unknown thickness in this section, but we assign the lower, exposed portion of the Hellnmaria Member, 472 ft (143.9 m) of limestone, to Sequence 1.

Sequence 1 consists of many small, meter-scale cycles. Evans (1997) recognized more than 40 such meter-scale cycles in the Sneakover Limestone and the lower map unit of the Hellnmaria. Such small cycles are clearly visible on Steamboat Mountain in the lower part of the Hellnmaria (Fig. 21), and they can also be seen throughout the Hellnmaria Member on Notch Peak (Fig. 20). Similar cycles occur in the southern House Range in the Lava Dam Member as high as the top of Sequence 6, at the top of the Millardan Series.

In Texas, the base of Sequence 1 clearly correlates with the major unconformity between the Dresbachian and Franconian stages. This unconformity is at the base of the Welge Sandstone Member, the lowest member of the Wilberns Formation, at 860 ft (262.1 m) above the base of the Cambrian (Fig. 14). (Measurements for the Threadgill Creek section are from Open-File descriptions of sections at the Texas Bureau of Economic Geology; these descriptions accompanied the monograph by Barnes and Bell, 1977). Because there is no precise biostratigraphic data to control the age of the top of Sequence 1 in Utah, correlation to Texas is problematic, but the Utah trilobite collection assigned to the *Taenicephalus* Zone is helpful. In the Threadgill Creek section, several thin stromatolite beds are evidence of shallowing conditions in the interval 1000–1014 ft (304.8–309.1 m), near the top of the Morgan Creek Limestone Member of the Wilberns Formation. At 1025 ft (312.4 m) is the base of the silty and shaly Point Peak Member of the Wilberns, and the influx of siliciclastic sediment probably reflects lowstand conditions, suggesting these strata are the base of Sequence 2. On the basis of these lowstand lithologies, we provisionally correlate the top of Sequence 1 at 1025 ft (312.4 m) in the Threadgill Creek section, at the base of the Point Peak Member. This level is near the middle of the *Idahoia* Zone (Longacre, 1970).

Package 1A—Corset Spring Lowstand and Sauk III Transgression

Package 1A is entirely within the Corset Spring Shale in the central House Range and within the upper part of the Steamboat Pass Shale in the southern House Range and northern Wah Wah Mountains. This package is 60 ft (18.3 m) thick in the central House Range and 50 ft (15.2 m) thick in the northern Wah Wah Mountains (Table 22). This package consists of cyclically interbedded shale and carbonate beds. Carbonate lithologies include lime mudstone, intraclast to peloid packstone to grainstone, and flat-pebble conglomerate. Stromatolites and thrombolites are common and typically are preserved with synoptic relief as overlying shale units covered them.

The base of Package 1A is a sequence boundary and is also the Sauk II-Sauk III boundary. This boundary lies within a single bed of intraclast grainstone that contains an irregular karst surface through its middle part (Fig. 18). Rounded *in situ* limestone clasts, fissures, and dissolution pockets are filled with autoclastic breccia, orange-weathering vadose silt, or sediment from the overlying lime mudstone succession that blankets the karstified surface. Locally, small faults with up to 3.5 inches (9 cm) of offset record early breakage and extension along the bed after lithification and prior to deposition of the overlying strata. This is the only known interval of subaerial exposure in the Corset Spring Shale and Steamboat Pass Shale. Strata overlying the karst surface are mostly thin beds of lime mudstone that drape topography and locally show synsedimentary folding.

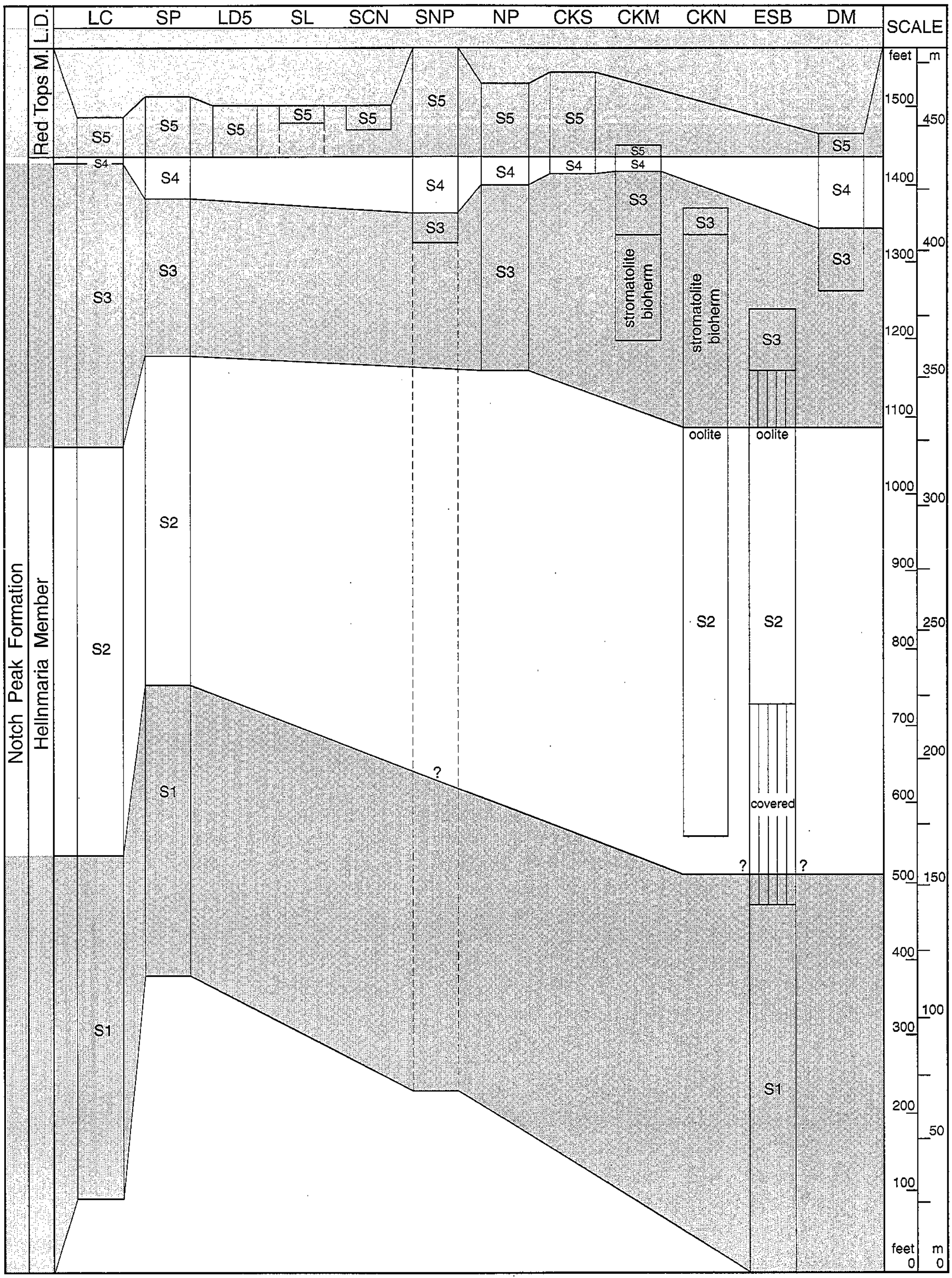


Figure 19. Correlation of thicknesses of Sequences 1–5 (S1-S5) for Hellnmaria Member among sections at Lawson Cove (LC), Steamboat Pass (SP), Lava Dam Five (LD5), Sevier Lake (SL), Sevier Lake Corral North (SCN), Sneakover Pass (SNP), Notch Peak (NP), Chalk Knolls South (CKS), Chalk Knolls Middle (CKM), Chalk Knolls North (CKN), East Shoreline Butte (ESB), and Drum Mountains (DM). For location of sections, see Figure 1. Odd-numbered sequences are shaded. Vertically ruled areas are thick covered intervals. Sections are described on CD-ROM. Dashed line for SNP shows thickness of Hellnmaria Member reported by Hintze et al. (1988). Sequence 5 at SL extends below interval measured and is shown by dashed line.

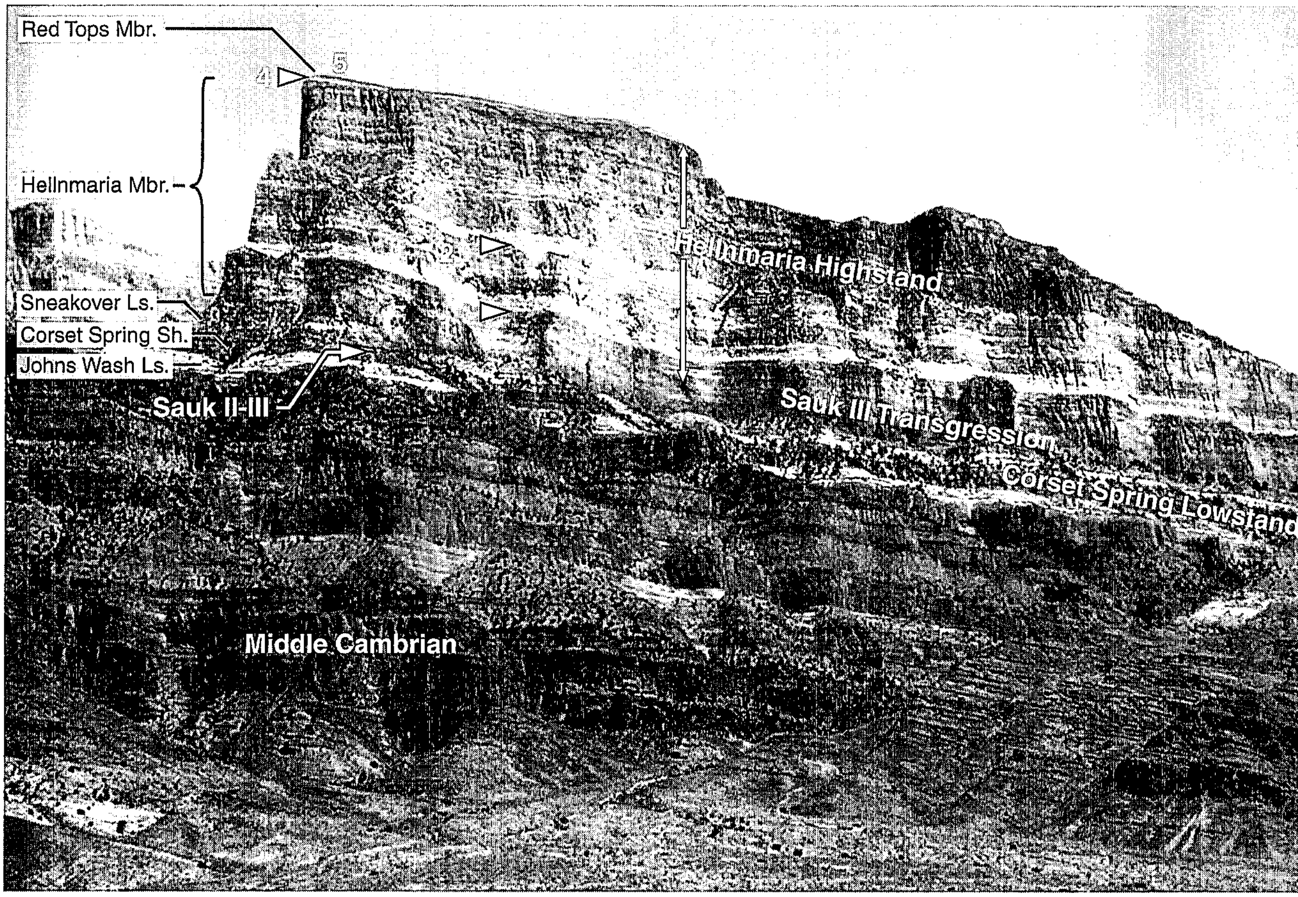


Figure 20. West face of Notch Peak from the Tule Valley Road showing lithostratigraphic and sequence stratigraphic units. Strata were thermally metamorphosed during intrusion of Jurassic Notch Peak Stock just north (left) of area shown. White triangles indicate sequence boundaries. 1 = Sequence 1, undifferentiated. 2 = Sequence 2. 3 = Sequence 3, base of which is a massive (dark) stromatolitic unit. 4 = Sequence 4, which is very thin and represented mostly by a white band near top of peak. 5 = lower part of Sequence 5, dark band at top of peak. Sauk II-Sauk III boundary interval lies in middle part of Corset Spring Lowstand. Upper part of Corset Spring Shale marks beginning of Sauk III Transgression, which continues into lower part of Hellnmaria Member. Hellnmaria Highstand comprises remainder of thick carbonates. Note numerous small-scale cycles in Hellnmaria Highstand. Relief in this view is more than 4000 feet (1220 m). Thickness of strata has not been measured here, but the Hellnmaria Member is 1203 ft (367 m) thick near Sneakover Pass (Fig. 1), the nearest measured section (Hintze et al., 1988, p. 21–23).

The top of Package 1A is a distinct surface that records a shift in facies. The middle part of the Corset Spring Shale contains interbedded shallow-water, high-energy limestones and shales that were deposited during slack water. Within a 2 ft (0.6 m) thick bed, silty dark brown-gray intraclast packstone to grainstone is overlain by medium gray lime mudstone to wackestone. The color change persists, and this surface can be correlated from Lawson Cove in the northern Wah Wah Mountains to Orr Ridge in the central House Range, ca. 37 miles (60 km). Above the surface, rocks are mostly lime mudstone interbedded with shale. We interpret this surface as a transgressive surface that reflects abrupt relative deepening of sea level. This surface also marks the base of Package 1B.

The karst surface at the base of this package records the lowest stand of sea level during the end of the Sauk II interval, and overlying strata record the Sauk III Transgression. Osleger and Read (1993) regarded this interval as a maximum flooding zone, but depositional facies remained fairly shallow. The abrupt deepening at the top of the package marks a renewed relative rise of sea level and the start of deposition of the succeeding package. Because of the abundant shale and relative shallow water sedimentation during deposition of Package 1A, we consider it to be a lowstand of sea level, particularly when compared with overlying rocks of Packages 1B and 1C, which record progressive deepening during the Sauk III Transgression (Fig. 2).

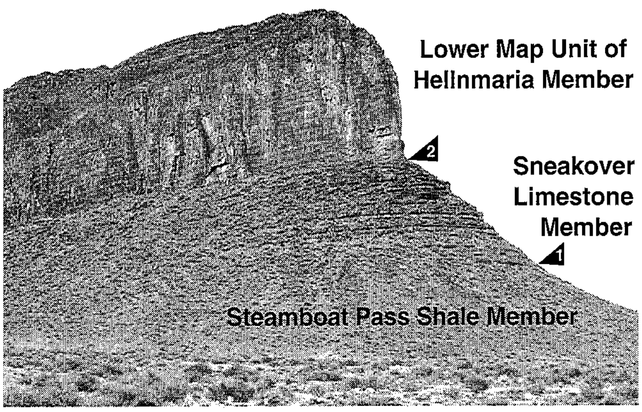


Figure 21. Meter-scale depositional cycles on west face of Steamboat Mountain, Steamboat Pass area, southern House Range. Cycles begin in Steamboat Pass Shale Member of Orr Formation (below 1), continue through Sneakover Limestone Member of Orr Formation (between 1 and 2) and through lower map unit of Hellnmaria Member of Notch Peak Formation (above 2). Base of Ptychaspid Biomere and Sunwaptan Stage is near middle of Sneakover Member. All strata illustrated are assigned to Sequence 1.

In Texas, Package 1A is probably missing in the unconformity at the base of the Welge Sandstone Member of the Wilberns Formation (Fig. 14).

Package 1B—Upper Part of Corset Spring Lowstand and Sauk III Transgression

The base of Package 1B is at the deepening event noted above. Package 1B includes the uppermost part of the Corset Spring Shale and laterally correlative strata of the Steamboat Pass Shale, and the package also includes the lower part of the Sneakover Limestone. The uppermost shale-and-limestone cyclic succession in the Corset Spring and Steamboat Pass shales is transitional with the overlying Sneakover Limestone, which includes thin to medium beds of burrowed lime mudstone to wackestone interbedded with thin to thick beds of shale. An echinoderm grainstone bed marks the lowermost bed of the Sneakover Limestone. Upward in the Sneakover, shale is much less common compared with the Corset Spring.

The most conspicuous feature of the Sneakover Limestone is a series of fourteen meter-scale cycles, each of which typically is ca. 1.5–2.0 meters thick. Cycles include resistant ledges of burrowed lime mudstone interbedded with thin-bedded silty carbonates that weather recessively. Some of the resistant beds have characteristic coloration. The fourth and eighth resistant cycles in this succession have dark gray bases and abruptly are overlain by light gray upper parts. The twelfth and thirteen resistant cycles are light yellow-gray on weathered surfaces, but fresh surfaces are light reddish gray. Based on this unique stratigraphic order, Evans (1996) correlated 14 cycles for more than 71 miles (115 km), indicating that these are allocyclic in origin (Evans, 1996). These strata contain *Elvinia* Zone trilobites, but overlying resistant cycles of dark lime mudstone contain faunas of the *Irvingella major* Trilobite Zone and are part of Package 1C. The top of Package 1B is at the top of the *Elvinia* Zone.

The top bed in Package 1B has a distinctive facies change in cycle fourteen in the Fish Springs Range (Fig. 1). Thin lime mudstone layers are interstratified with silty orange partings to thin laminae. Cycle 14 is thicker there than in areas to the south, and an angular flat-pebble conglomerate caps the ledge. This cycle was deposited in apparently shallow water depths that seem to have promoted thicker accumulation of sediment, and the upper surface of cycle 14 essentially had aggraded to within normal storm wave base. We interpret this event as a possible lowering of sea level, but it is equally possible that the dynamics of an increased sedimentation rate could have outstripped either continued relative sea-level rise or stillstand (Fig. 2).

Overall, Package 1B in the Fish Springs Range is only half as thick as in the central and southern House Range and in the northern Wah Wah Mountains. We consider that Packages 1A and 1B essentially lap onto the southern flank of the Tooele Arch in the Fish Springs Range. We cannot accurately determine the thickness of these packages in the Fish Springs Range to subdivide them because neither of the lower surfaces that bound these packages has been found there. In the central and southern House Range and in the northern Wah Wah Mountains, however, Package 1B ranges from 140–145 ft (42.7–44.2 m) thick.

The origin of meter-scale cycles in the Sneakover Limestone is contentious. Most Cambrian meter-scale cycles aggrade to sea level and have tidal-flat facies at cycle tops. Because cycles in the Sneakover Limestone are entirely subtidal, Osleger (1991) argued that storm wave base limited the aggradation of cycles. Evans (1997) considered that cycles need not have been limited, but influxes of silt, perhaps associated with small-scale fluctuations of sea level, were interspersed in the succession so that sediments essentially comprise a continuous record. Regardless of their origin, these cycles are a prominent feature of the Sauk III Transgression as it is expressed in Great Basin successions.

The base of Package 1B is probably at the base of the Welge Sandstone in the Threadgill Creek section in Texas, at 860 ft (262.1 m) in the measured section (Fig. 14). Based on its biostratigraphic position, the top of Package 1B is at 913 ft (278.3 m) in the section, so the package is 53 ft (16.2 m) thick at Threadgill Creek.

Package 1C—Culmination of Sauk III Transgression

The base of Package 1C is the top of cycle 14 in the Sneakover Limestone Member of the Orr Formation. The top of Package 1C is poorly known, but we interpret that it occurs at the base of an interval of zebra-rock dolomite in the lower Hellnmaria Member. Package 1C includes faunas of the *Irvingella major* Zone and of the overlying *Taenicephalus* Zone. The *Taenicephalus* Zone is known from few collections, so its top is not delineated precisely. The thickness of Package 1C is approximately 540 ft (165 m) at Steamboat Pass.

Depositional facies of this package are comparable to strata of the lower Sneakover, and cycles of lime mudstone interbedded with argillaceous lime mudstone continue upward (Fig. 21). A succession of more than 40 cycles is found from the base of the Sneakover Limestone into the lower map unit of the Hellnmaria Member (Evans, 1997, Fig. 12). Rowell and Brady (1976) first recognized that beds containing the *Irvingella major* fauna are dark gray (darker than underlying strata of Package 1B), and they essentially form a blanket deposit over much of the eastern Great Basin. Two resistant dark gray ledges contain the *Irvingella major* fauna, but overlying strata vary markedly from western Utah to eastern Nevada.

A distinct deepening event is recorded in Package 1C. In Utah successions the deepest lithofacies of Sequence 1 (and possibly of the entire succession discussed in this report) is a few feet above the *Irvingella major* Zone in the upper part of the Sneakover Limestone. In the House Range and Wah Wah Mountains, strata above the *Irvingella major* Zone show deepening, but sediments continued to accumulate and to develop into the thick carbonates of the Hellnmaria Member. A few cycles of dense, black spiculitic lime mudstone crop out in slopes at the base of the Hellnmaria Member (Fig. 21) and indicate deep subtidal conditions. This deepening event is shown on the sea-level curve of Figure 2.

The contact between the Orr Formation and Notch Peak Formation (base of the Hellnmaria Member) is mapped as a change from slope-forming to cliff-forming strata (Hintze et al. 1988; see Fig. 21 herein). There is no significant lithologic change between these formations. Cliff-forming strata of the lower map unit of the Hellnmaria Member are uniform cycles of lime mudstone that lack the recessive weathering beds that characterize some of the Sneakover Limestone. Through much of the lower map unit of the Hellnmaria, successions of deep-subtidal cycles are progressively overlain by shallower-water cycles. A succession of meter-scale cycles of zebra dolomite and dolomitized oncoid grainstone are provisionally regarded as the base of Sequence 2. These strata record a shift toward shallow-water intertidal to supratidal facies and reflect an interval of minimum accommodation.

In summary, renewed deepening at the base and top of the *Irvingella major* Zone reflects both rapid rates of sea-level rise during the Sauk III transgression and sustained rapid rates of subsidence. In Utah, we characterize the interval above the *Irvingella major* Zone as catch-up and keep-up carbonate sedimentation (Sarg, 1988). Near the top of Sequence 1, sediment deposition rates exceeded subsidence (accommodation) rates, so that by the beginning of Sequence 2 the depositional environment had shallowed to peritidal conditions in the Lawson Cove and Steamboat Pass areas.

At Threadgill Creek in Texas, the base of Package 1C is at 913 ft (278.3 m), at the base of the *Irvingella major* Zone (Fig. 14), and the top is questionably placed at the base of the Point Peak Member at 1025 ft (314.4 m). Package 1C is thus 112 ft (34.1 m) thick.

SEQUENCE 2—LOWER PART OF HELLNMARIA HIGHSTAND

Sequence 2 is within the middle part of the Hellnmaria Member of the Notch Peak Formation (Fig. 2). Sequence 2 began with a possible lowstand or stillstand in the Steamboat Pass and Lawson Cove sections. Steamboat Pass is a topographic feature that is formed by shaly lowstand strata of the Steamboat Pass Member. Steamboat Mountain, on the north side of the pass, is formed by resistant strata of the upper part of Sequence 1, the lower map unit of the Hellnmaria Member. The break in slope above the top of Steamboat Mountain (Fig. 21) is formed by less resistant zebra-rock dolomite at the base of the middle map unit of the Hellnmaria. Hintze et al. (1988, p. 25–26, units 7–9) described zebra-rock dolomites in the lower part of this middle map unit as occurring through ca. 128 ft (39 m) of strata in the Steamboat Pass section. Hintze et al. (1988, p. 27, unit 3) described zebra-rock dolomite occurring at three horizons in their lowest 220 ft (67.0 m) unit of dolomite in the Hellnmaria at Lawson Cove, although zebra rock does not occur through the whole unit. Zebra-rock dolomite (Fig. 22) is quarried extensively as ornamental stone in the Steamboat Pass and Lawson Cove areas and is made into attractive obelisks, spheres, eggs, bear fetishes, etc. by lapidaries; these objects are found in rock shops in many parts of the country.

Zebra-rock dolomite consists of alternating centimeter-scale bands of dark gray to black recrystallized dolomitic sediment and white bands of dolomitic cement. Meter-scale beds commonly form cycles that may be capped by thin layers of recrystallized oncoids. Oncoids commonly are up to 1 cm in diameter and typically are in grain-to-grain contact within a white dolomitic cement matrix. We interpret this facies as recrystallized tidal-flat deposits, essentially microbial mats and oncoids, deposited at water depths ranging from shallow subtidal to supratidal. We interpret this succession as a sea-level lowstand or stillstand, although this unusual lithology has not been studied in detail. We consider this putative lowstand to be less clearly established than other lowstand intervals discussed in this report. Zebra rock may have formed during a stillstand (rather than a lowstand) when conditions of minimum accommodation persisted for an extended period.

Figure 22. Zebra-rock dolomite in lower part of Hellnmaria Member of Notch Peak Formation in the Lawson Cove area. White crystalline dolomite cement and black dolomite bands are parallel to original bedding. Swiss Army knife near top of image is 3.5 inches (9 cm) long.

Because of the difficulties recognizing the top of Sequence 1, the base of Sequence 2 is poorly known. In the East Shoreline Butte section the base of Sequence 2 may be in the thick covered interval, unit 15. This stratigraphic interval is not exposed in other nearby sections but can be seen on the west face of Notch Peak (Fig. 20).

The top of Sequence 2 is also less well understood than the tops of our other sequences. At Lawson Cove the top of Sequence 2 is placed just below a second interval of zebra-rock dolomite in the Hellnmaria Member, in unit 11 of Hintze et al. (1988, p. 27). We provisionally assign underlying strata, units 3–10, to Sequence 2, so its thickness is 525 ft (160.0 m). This part of the Hellnmaria at Lawson Cove and at Steamboat Pass has several occurrences of the monoplacophoran mollusk *Matthevia* (Hintze et al., 1988, Fig. 3). There is no description of zebra rock near the occurrences of *Matthevia* at Steamboat Pass, but we infer that the top of Sequence 2 is in the upper part of the Hellnmaria Member that is characterized by this fossil. At Steamboat Pass we tentatively assign Hellnmaria units 7–19 of Hintze et al. (1988, p. 25–26) to Sequence 2; these strata are 422 ft (128.6 m) thick (Table 18).

We are not confident that the top of the third-order sequence of Osleger and Read (1993) is the same as the top of our Sequence 2 (Fig. 15). The first reason is that those authors did not identify their boundary as a specific horizon in a measured section. The second reason is that they based their interpretation on Fisher Plots, whereas we use other criteria to identify sequence boundaries. Nevertheless, at about the level where Osleger and Read (1993) placed the top of their third-order sequence, we recognize in Tule Valley an interval of shallow marine facies that we interpret as the boundary between Sequences 2 and 3.

This shallow facies is marked by high-energy ooid grainstones that occur above a thick interval of low-energy, deep subtidal lime mudstone near the top of the East Shoreline Butte section (unit 32) and within the Chalk Knolls North section (units 25, 27; see section descriptions on CD-ROM). Insoluble residue data for the upper part of the East Shoreline Butte section (Table 10, Fig. 16) indicate an abrupt, five-fold increase in fine quartz sand associated with this ooid grainstone. We infer that these ooid grainstone beds record shallowing of the depositional environment and that this interval can be correlated with the zebra-rock dolomites at Steamboat Pass and Lawson Cove. These ooid grainstones and other shallow-marine deposits form the upper white band on the west face of Notch Peak (Fig. 20). We place the top of Sequence 2 just below these ooid grainstone intervals, which are assigned to the base of Sequence 3, resulting in a thickness of at least 348 ft (106.1 m) for Sequence 2.

Sequence 2 began with a lowstand or stillstand that represents an accommodation minimum. Overlying strata record a prolonged interval characterized by a moderate but uniform rate of accommodation (Fig. 2). The zebra rock and ooid grainstone interval at the base of Sequence 3 may record a lowstand or interval of reduced accommodation.

Part of Sequence 2 contains biostratigraphically significant conodonts. At East Shoreline Butte the base of Sequence 2 may be within the covered interval, unit 11 (CD-ROM). The base of the *Proconodontus tenuiserratus* Zone is in unit 24, and the base of the *P. posterocostatus* Zone is in unit 26. The ooid grainstone at the base of Sequence 3 is unit 32. At Chalk Knolls North the base of Sequence 2 is not exposed, but the base of the *P. tenuiserratus* Zone is in unit 12, and the base of the *P. posterocostatus* Zone is in unit 19. The lowest ooid grainstone (base of Sequence 3) is in unit 22. Thus Sequence 2 begins below the base of the *Proconodontus tenuiserratus* Zone and ends in the lower part of the overlying *P. posterocostatus* Zone in both of these sections. No conodonts have been recovered from the coeval dolomite facies of the Hellnmaria at Steamboat Pass and Lawson Cove, so no biostratigraphic correlation is possible from those sections to strata at East Shoreline Butte and Chalk Knolls North. One trilobite collection from this sequence near the base of the Chalk Knolls North section is assigned to the *Saratogia* Zone.

It is possible to correlate to Texas strata using these conodont zones. The base of Sequence 2 may be at the base of the Point Peak Member of the Wilberns Formation in the Threadgill Creek section in Texas, at 1025 ft (312.4 m) in the measured section of Barnes and Bell (1977). This horizon is below the base of the *Proconodontus tenuiserratus* Zone (Fig. 14). The base of the *P. posterocostatus* Zone is at 1200 ft (365.8 m), the top is at 1267 ft (386.2 m) in the Threadgill Creek section, and the top of Sequence 2 may be in the lower part of the zone. There are no obvious truncation surfaces in this interval, but there are stromatolites at about 1210–1215 ft (368.8–370.3 m). These stromatolites may indicate the shallowing event associated with the base of Sequence 3, and we interpret them as such herein, although with reservation.

If the correlations concerning Sequence 3 are correct as discussed above, it is possible to tie into the trilobite biozonation in the Threadgill Creek section. Longacre (1970) reported no trilobite collections from this part of the section, but collections made by Miller and Stitt have clarified the biozonation (Fig. 14). The base of the *Saukia* Zone is at 1139 ft (347.2 m). The base of the *Saukiella pyrene* Subzone is at 1205 ft (367.3 m), so the top of Sequence 2 appears to be close to, but perhaps slightly above, the base of this subzone. Sequence 2 appears to comprise ca. the upper half of the *Idahoia* Zone, all of the *Ellipsocephaloides* Zone, and the lower part of the *Saukia* Zone. At Threadgill Creek this interval is 1025 ft to ca. 1210 ft, or 185 ft (312.4 m to ca. 368.8 m, or 56.4 m).

SEQUENCE 3—UPPER PART OF HELLNMARIA HIGHSTAND

Sequence 3 comprises the upper part of the Hellnmaria Member but does not include the highest beds (Figs. 2, 19). In the Chalk Knolls and East Shoreline Butte area the base is characterized by a thin interval of ooid grainstone within a thick succession of upper Hellnmaria deep-water, cherty lime mudstone. The ooid grainstone records the shallowing event that we believe Osleger and Read (1993) used to separate the Hellnmaria into two third-order sequences. The ooid grainstone and associated grainstones and other lowstand deposits are visible as the highest of three white bands (all three bands are lowstand deposits) on the west face of Notch Peak (Fig. 20). The top of Sequence 3 is a sharp truncation surface that we have identified at Chalk Knolls Middle, Chalk Knolls South, Sneakover Pass, and Steamboat Pass. At Chalk Knolls Middle this truncation surface is at the top of unit 15. At Sneakover Pass we place the sequence boundary at the lower of two truncation surfaces that are 2 ft (0.6 m) apart, at the base and top of unit 4.

Sequence 3 is 553 ft (162.5 m) thick in the Chalk Knolls area and is entirely limestone (Table 18). Another complete limestone section of Sequence 3 is at Sneakover Pass, but we have studied only the top few beds of the Hellnmaria in this section (CD-ROM). Sequence 3 is dolomite in the southern House Range, northern Wah Wah Mountains, and Drum Mountains.

We infer that the base of Sequence 3 is at the bottom of the zebra-rock dolomite in unit 11 (Hintze et al., 1988, p. 27) at Lawson Cove. The top of Sequence 3 at Lawson Cove is in stromatolitic dolomites below the base of our measured section. We can demonstrate that the upper 5 ft (1.5 m) of the Hellnmaria contains fauna diagnostic of Sequence 4. Provisionally, we assign to Sequence 3 described units 11–15 and all but the upper 5 ft (1.5 m) of unit 16 of Hintze et al. (1988, p. 27) at Lawson Cove. The base of Sequence 3 at Steamboat Pass is placed at the base of unit 19 (Hintze et al., 1988, p. 25) but may be somewhat lower or higher. The top of Sequence 3 is at a truncation surface at the top of unit 4.

The base of Sequence 3 is somewhat above the base of the *Proconodontus posterocostatus* Zone. Conodonts of this zone occur in Sequence 3 at Notch Peak, Chalk Knolls North, at Drum Mountains, and at a sample 2 ft (0.6 m) above the base of the Sneakover Pass section (CD-ROM). The truncation surface at top of Sequence 3 is overlain by strata that contain conodonts of the *Proconodontus muelleri* Zone at Steamboat Pass, Sneakover Pass, and Chalk Knolls South. Thus Sequence 3 is entirely within the *P. posterocostatus* Zone.

In the Threadgill Creek section of Texas, the base of Sequence 3 is not completely clear but the top is. The top of Sequence 3 in Utah is a double truncation surface, and a similar double truncation surface is present at this level in Texas. There also, the sequence is entirely within the *Proconodontus posterocostatus* Zone. Sequence 3 is entirely within the *Saukiella pyrene* Trilobite Subzone.

Sequence 3 has two distinguishing characteristics: 1) it has abundant stromatolites, and 2) it is usually terminated by an unconformity at one or more closely spaced truncation surfaces. The upper part of the Hellnmaria at Lawson Cove is a thick stromatolite bioherm, as is the upper map unit of the Hellnmaria at Steamboat Pass (Hintze et al., 1988, p. 25, units 24–26). Units 11–13 (Hintze et al., 1988, p. 22) of the Hellnmaria at Sneakover Pass are thick stromatolite units. Sequence 3 at Chalk Knolls North and Chalk Knolls Middle includes thick stromatolite units. This lithology is overlain by alternating relatively thin dark and light strata that appear to document a shallowing event that reached peritidal conditions and exposure as accommodation was filled at the top of the sequence (Fig. 23). The thick stromatolitic unit and the overlying light and dark bands are also visible on the west face of Notch Peak (Fig. 20). Sequence 3 in the Oklahoma aulacogen includes a thick stromatolite unit in the upper Fort Sill Limestone (Stitt, 1977, p. 55, unit 12). This unit is overlain by peritidal strata in the lower unit of the Signal Mountain Limestone (Stitt's unit 13), but these strata contain no diagnostic conodonts, so their sequence assignment is questionable. Overlying strata of Stitt's unit 14 are part of Sequence 4, based on the occurrence of *Proconodontus muelleri*. Sequence 3 has some thin intervals of stromatolites or thrombolites in the Threadgill Creek section in Texas.

The unconformity at the top of Sequence 3 is present in the southern House Range, central House Range, in central Tule Valley, and in Texas. Donovan (2001) recognized an unconformity at the top of the Fort Sill Formation in the Oklahoma aulacogen, and he stated that this unconformity could be traced across the Laurentian craton. The unconformity he discussed may be the unconformity that we recognize between our Sequences 3 and 4. A more likely interpretation is that the unconformity is slightly older, equivalent to the top of the thick stromatolites, unit 34 at Chalk Knolls North and unit 1 at Chalk Knolls Middle. In this scenario, the peritidal beds of Stitt's unit 13 would be equivalent to the light-dark banded, peritidal strata of units 35–41 at Chalk Knolls North and to units 2–15 at Chalk Knolls Middle. In all of these areas the overlying strata of Sequence 4 contain *Proconodontus muelleri*. If this interpretation of the Oklahoma succession is correct, there might be an unconformity at the top of the stromatolitic unit (top of Fort Sill Formation) and a second unconformity at or slightly below the base of the *Proconodontus muelleri* Zone (top of Stitt's unit 13).

Sequence 3 began with an interval of reduced accommodation recorded by the upper interval of zebra rock at Lawson Cove and by ooid grainstone in the Chalk Knolls area. Much of the sequence consists of stromatolitic and other shallow subtidal to peritidal strata, suggesting a prolonged period of low accommodation but not necessarily a lowstand of sea level. During this interval, which we refer to as the Hellnmaria Highstand, carbonate sedimentation essentially kept pace with accommodation. There is no indication of significant sea level fall during deposition of all of Sequences 1 through 3. In contrast, the top of Sequence 3 is a truncation and surface of unconformity locally and regionally, suggesting at least a regional and probably interregional relative drop in sea level at the end of the sequence.

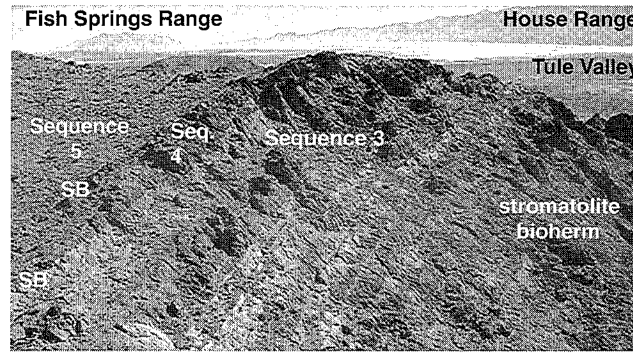


Figure 23. Northward view of sequence stratigraphic units in Chalk Knolls Middle section, central Tule Valley. Sequences 3 and 4 are upper part of thick Hellnmaria Member; Sequence 5 is in Red Tops Member. SB = sequence boundary. Close-up view of lower SB (from 50 m farther south) is in Figure 28.

SEQUENCE 4

Sequence 4 is demonstrably an unconformity-bounded interval that includes the top beds of the Hellnmaria Member, and it is much thinner than the lower sequences. Sequence 4 is thickest in the Drum Mountains, where it is 95 ft (29.0 m) thick in a poorly exposed dolomite facies. In limestone facies it is thickest at Steamboat Pass, where it is 44 ft (13.4 m) thick (Fig. 24). There, Sequence 4 begins in the upper Hellnmaria at the base of lithologic unit 5, and it ends at the Hellnmaria-Red Tops contact. Both boundaries are truncation surfaces. Sequence 4 apparently is thinnest at Lawson Cove, where stromatolitic dolomite is well exposed below the base of the described section. Because this lithology typically does not produce conodonts, it was not studied and thus is poorly documented, but we consider it to be the top of Sequence 3. Above the stromatolitic beds is a 5 ft (1.5 m) interval of poorly exposed, non-stromatolitic dolomite that is assigned to Sequence 4. The top of Sequence 4, the Hellnmaria-Red Tops contact, is covered at Lawson Cove, and the lowest beds of the Red Tops are very poorly exposed. The thickness of this sequence in various sections is recorded in Table 23, but typically it ca. 20 ft (6 m) thick.

At Steamboat Pass, Chalk Knolls Middle, Chalk Knolls South, and Sneakover Pass, the base of Sequence 4 is a karst truncation surface that is clearly below the Hellnmaria-Red Tops contact. At Steamboat Pass the top bed of Sequence 3 is a fine peloid grainstone that is truncated by a planar surface (Fig. 25) and is overlain by lime mudstone at the base of Sequence 4; this surface is 44 ft (13.4 m) below the top of the Hellnmaria. Near the head of the canyon a few hundred meters to the northeast, this contact is a microkarst surface with several centimeters of local relief. However, along strike the contact is mostly planar, suggesting that any relief was eroded away during transgression at the start of Sequence 4. Only a few places along strike preserve irregularities where abrasion during the subsequent transgression did not cut low enough to remove all of the microkarst relief. Hintze et al. (1988, p. 25) identified this 44 ft (13.4 m) interval as unit 27 of their Steamboat Pass measured section and assigned it to the base of the Red Tops Member. Miller et al. (2001, p. 58) reassigned this interval to the top of the Hellnmaria Member.

The base of Sequence 4 usually has a double truncation surface in sections north of Steamboat Pass. The two truncation surfaces, commonly with microbial strata between them, is a unique feature of the base of Sequence 4. This interval is essentially a thin lowstand, but we simply regard it as a sequence boundary zone. At Chalk Knolls South the base of Sequence 4 is a karst surface that truncates the top of Sequence 3, which is a fine peloid grainstone 20 ft (6.1 m) below the top of the Hellnmaria. The lower of two truncation surfaces has scalloped features that superficially resemble regularly spaced ripple marks (Fig. 26), but they have steep to vertical sides with 2–4 cm of relief and thus are not ripples. Instead, these features were produced by karst dissolution. The overlying basal bed of Sequence 4 is 1–1.5 ft (0.3–0.5 m) thick and includes a graded succession of oncoids up to 3 cm in diameter; the top of the bed is a second irregular truncation surface (Fig. 27). Overlying strata include intervals of ooid grainstone with foreset bedding, grainstone to packstone, and two units of stromatolitic boundstone (see described section). The top of the second stromatolitic unit is the top of the Hellnmaria and the top of Sequence 4.

A similar lithologic succession and double truncation surface is present at the base of Sequence 4 at the Chalk Knolls Middle section. The top bed of Sequence 3 is a fine peloid grainstone with an irregular microkarst surface with scalloped relief forms. The overlying oncolites surround pinnacle stromatolites that grew upward from the tops of some of the scalloped microkarst relief forms (Figs. 23, 28). Our interpretation is that production of carbonate sediment filled accommodation at the end of Sequence 3, and subsequent relative sea-level fall exposed the carbonate platform to subaerial dissolution, resulting in the low karst pinnacles. As the karst features were flooded during the subsequent relative rise of sea level, stromatolites were established on the tops of the pinnacles and grew upward rapidly as water depth increased. These stromatolites rest on the base of Sequence 4. Oncoids formed penecontemporaneously and ultimately buried the pinnacle stromatolites. Laterally, perhaps 50 m along outcrop at Chalk Knolls Middle, stromatolites were more fully developed as discrete hemispheric bioherms. At the top of this oncoid grainstone and stromatolite bed is the second truncation surface. The large stromatolites were beveled, but elsewhere the surface is irregular. The closely spaced double truncation surfaces delineating unit 1 at Chalk Knolls South probably are the same surfaces at the base and top of unit 4 at Sneakover Pass (see description of section on CD-ROM), which also contains stromatolites and is strongly

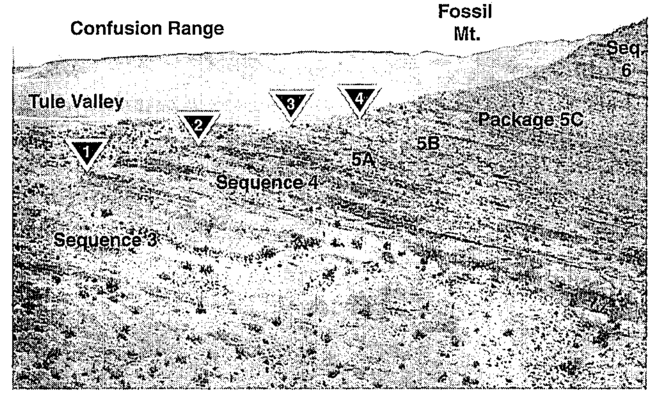


Figure 24. Westward view of sequence stratigraphic units exposed in Steamboat Pass section, southern House Range. Lowest strata are assigned to Sequence 3. 1 = base of Sequence 4. 2 = base of Package 5A at base of Red Tops Member. 3 = base of Package 5B. 4 = base of Package 5C at base of Lava Dam Member. Base of Sequence 6 is unclear at this distance.

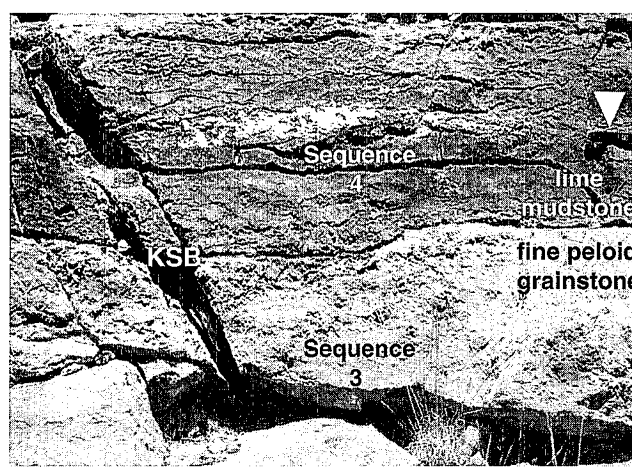


Figure 25. Karst sequence boundary (KSB) between Sequences 3 and 4 at position 1 on Figure 24, Steamboat Pass section in southern House Range. Triangle points to Swiss Army Knife for scale, 3.5 inches (9 cm) long.

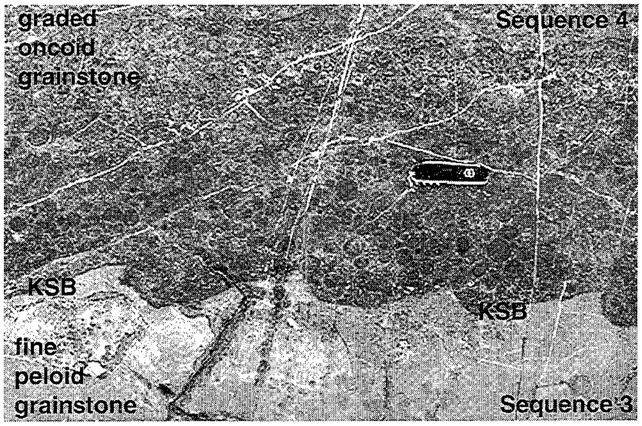


Figure 26. Base of Chalk Knolls South section, central Tule Valley. KSB = Karst Sequence Boundary between Sequences 3 and 4. Swiss Army knife is 3.5 inches (9 cm) long. Compare with Figure 25.

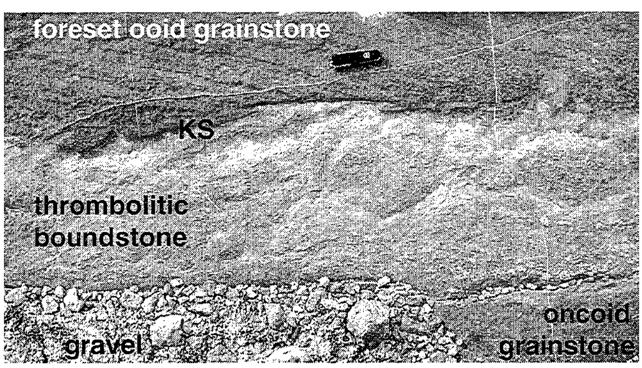


Figure 27. Irregular karst surface (KS) between described units 2 and 3, at ca. 3 ft (0.9 m) in Chalk Knolls South section. All strata are from lower part of Sequence 4. Oncoid grainstone is same bed shown in upper part of Figure 26 but is ca. 50 m to the north. Two karst surfaces in Figures 26 and 27 are correlated with the double truncation surfaces shown on Figure 29 at Sneakover Pass and on Figure 30 at Threadgill Creek, Texas. This karst surface is slightly below the lowest occurrence of Proconodontus muelleri. *Swiss Army knife near top of image is 3.5 inches (9 cm) long.*

burrowed (Fig. 29). This burrowed unit occurs also in described unit 14 at the Notch Peak section, although truncation surfaces are not evident, so there may be no hiatus at the base of Sequence 4 at that section.

The pattern of a double truncation surface with intervening microbial rocks is repeated in the Threadgill Creek section in Texas. The lower truncation is planar to irregular along strike, is stained red with iron oxide, and it formed a base for growth of thrombolites (Fig. 30). The upper surface of the thrombolites is irregular and appears to have formed by karst dissolution.

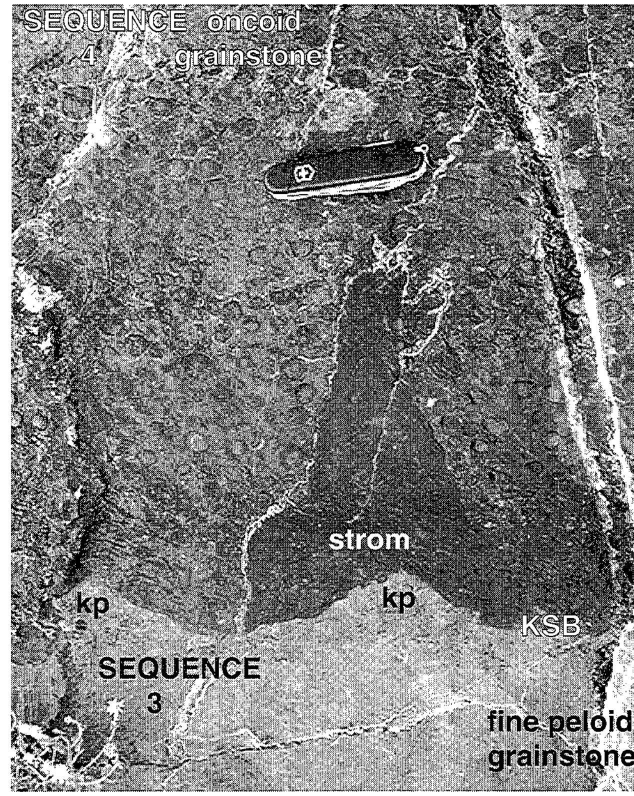


Figure 28. Karst sequence boundary (KSB) separating Sequences 3 and 4 at 901 ft level in Chalk Knolls Middle section (lower SB on Fig. 23, 50 m to north). Karst pinnacles (kp) formed by dissolution during relative drop in sea level. During subsequent relative rise in sea level, stromatolite (strom) grew upward from karst pinnacle until it was covered by oncoids. Compare with Figure 26. Swiss Army knife is 3.5 inches (9 cm) long.

The top of Sequence 4 is also a truncation surface in all Utah sections where it is exposed, and it is also the Hellnmaria-Red Tops contact. The top bed of Sequence 4 is a thin but prominent, light-colored stromatolite biostrome at the top of the Hellnmaria Member in the central House Range-central Tule Valley area. This biostrome is 3 ft (0.9 m) thick at Sneakover Pass (Fig. 32), 5 ft (1.5 m) at Chalk Knolls South, and 14 ft (4.3 m) thick at Chalk Knolls Middle, and it occurs directly below the brown-weathering Red Tops Member. This light unit is conspicuous below the Red Tops Member slightly north of Highway 6-50 and a little east of Skull Rock Pass. This stromatolitic biostrome forms a light band just below the top of Notch Peak (Fig. 20), the top of which is formed by the Red Tops Member (Hintze, 1974a). At Chalk Knolls Middle, stromatolites are remarkably well preserved in three-dimensional blunt pinnacles just a few centimeters below the Hellnmaria-Red Tops contact.

Conodont faunas from Sequence 4 are assigned to the *Proconodontus muelleri* Zone; the base of the zone is essen-

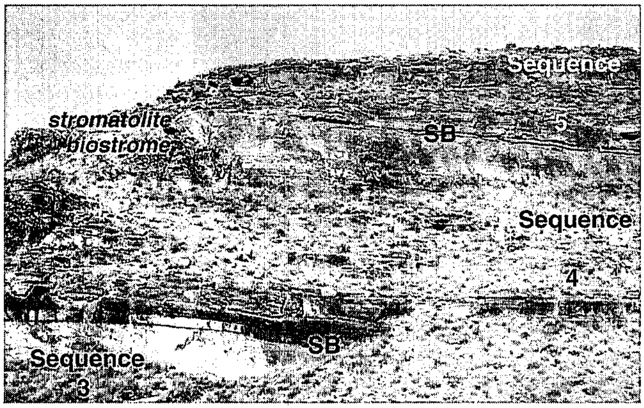


Figure 29. Eastward view of lower part of Sneakover Pass section. Sequences 3 and 4 are top strata of thick Hellnmaria Member. Base of Sequence 5 is base of Red Tops Member. Sequence boundary (SB) at base of Sequence 4 is a double truncation at 38 and 40 ft in described section (CD-ROM). Stromatolitic biostrome is at same stratigraphic level as white, stromatolitic band near top of Figure 20.

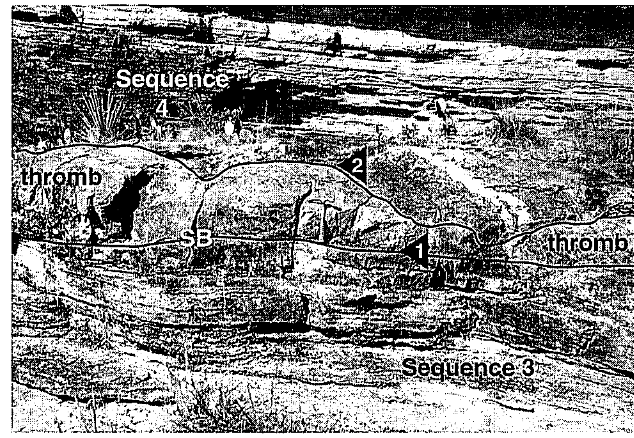


Figure 30. Thrombolite bed (thromb) in San Saba Member of Wilberns Formation, Central Texas. 1 = irregular truncation surface at base of thrombolite bed, interpreted as base of Sequence 4 (SB). 2 = irregular (probably karst) truncation surface above thrombolite bed, at 1265 feet in Threadgill Creek section. Truncation surfaces emphasized by black lines. Compare with double truncation surface at this level in Sneakover Pass section, Figure 29, and with Figures 25, 26, and 28. Hammer at center of photo is 11 inches (28 cm) tall.

tially at the base of the sequence, but the zone continues into the lower part of Sequence 5. One collection of trilobites from Sequence 4 at Chalk Knolls Middle is assigned to the *Saukiella pyrene* Subzone of the *Saukia* Zone. The upper part of Sequence 4 at Steamboat Pass is in the Red Tops Member and contains trilobites that are assigned to the *Saukiella junia* Subzone (Hintze et al., 1988).

The base of Sequence 4 in Texas is the lower truncation surface (Fig. 30) at 1263 ft (385.0 m). The base of the *Proconodontus muelleri* Zone is the next bed above the thrombolite unit, at 1267 ft (386.2 m), and the top of the sequence is in the upper part of this zone. The top of Sequence 4 is difficult to identify, but it may be at about 1300 ft (396.2 m) in the Threadgill Creek section in an interval of coarse grainstone beds, some of which are red. Several beds in this interval have abundant trough or herringbone cross-stratification, but no truncation surface is evident. The lower part of Sequence 4 is in the *Saukiella pyrene* Subzone of the *Saukia* Zone, and the upper part is in the *Saukiella junia* Subzone (Fig. 14), as in Utah.

Sequence 4 records the filling of accommodation at the top of the Hellnmaria Highstand. Sequence 3 includes quite shallow lithofacies, and in Utah the white beds near the top (Fig. 23) are peritidal to supratidal. The widespread truncation surfaces that delineate Sequence 4 indicate a widespread regressive event that is followed by the Red Tops Lowstand.

UPPER MILLARDAN SEQUENCES

Sequences 5 and 6 comprise the upper part of the Millardan Series, although the thin interval of Package 6C is assigned to the overlying Ibexian Series. Strata include the Red Tops Member and approximately the lower half of the Lava Dam Member. A graphic summary of the thicknesses of Packages 5A and 5B in various sections is shown on Figure 19; Package 5C and Sequences 6–14 are summarized graphically on Figure 31. Table 23 (CD-ROM) records for each measured section the intervals of Notch Peak and House strata that are assigned to each of the 14 sequences and their constituent packages.

SEQUENCE 5

Sequence 5 comprises the Red Tops Member and the lowest part of the Lava Dam Member. The base of Sequence 5 is a truncation surface where it is exposed at Steamboat Pass, Sneakover Pass (Fig. 32), and in the Chalk Knolls area. The top of Sequence 5 is at the base of a thin interval of intraclast grainstone to packstone exposed at Lawson Cove, Lava Dam Five, and perhaps at Steamboat Pass.

The Red Tops Member consists of high-energy deposits that include ooid grainstone, fine grainstone with cross-laminated sets, flat-pebble conglomerate with clasts of the previous lithologies, and stromatolitic boundstones. We interpret these lithologies as lowstand deposits and apply the term Red Tops Lowstand to the interval that comprises the Red Tops Member (Fig. 3). The Red Tops-Lava Dam contact typically is covered, but it is well exposed at Sevier Lake Corral North, where it is conformable and appears to record upward-deepening conditions, indicated by the transition from grainstones (Red Tops) to overlying lime mudstone (Lava Dam). The Red Tops Lowstand is thin on the Wah Wah Arch at Lawson Cove, thickest in the House Range Embayment at Sneakover Pass and Chalk Knolls South, and thin on the south flank of the Tooele Arch at the Drum Mountains section.

Lateral equivalents of the Red Tops Lowstand also have features consistent with lowstand deposition. In slope deposits of the Hales Limestone at Tybo Canyon in the Hot Creek Range, Nevada (Cook et al., 1989), strata of this age include debris-slide breccias within a stratigraphic interval that is brown in color like the Red Tops Member. In contrast, immediately underlying and overlying strata of the Hales Limestone are gray and lack debris-slide breccias. Lowering of sea level during the Red Tops Lowstand resulted in collapse of the upper slope or shelf edge in Nevada, leading to the formation of these debris-slide breccias; the mechanism for producing such breccias was discussed by Miller (1992, p. 404). Coeval strata of the Whipple Cave Formation in the Egan Range, Nevada are also shallow, high-energy lithologies and were deposited on the same carbonate platform as in the Ibex area (Taylor et al., 1989). Stitt and Straatmann (1997, p. 95) found no trilobites representing the *Saukiella junia* Subzone in the Deadwood Formation in the Black Hills area, South Dakota. These strata are generally a very shallow siliciclastic lithofacies. They speculated that the absence of this fauna may have been due to a hiatus during the Red Tops Lowstand. This lowstand can also be recognized on the craton in Texas.

The boundaries of Sequence 5 are well characterized relative to biostratigraphic units. The base is in the upper part of the *Proconodontus muelleri* Zone. The sequence includes all of the *Eoconodontus notchpeakensis* Subzone and most of the *Cambrooistodus minutus* Subzone of the *Eoconodontus* Zone. The base of Sequence 5 is slightly above the base of the *Saukiella junia* Subzone, and the top is within the upper part of the *Saukiella serotina* Subzone of the *Saukia* Zone (Fig. 3).

The boundaries of Sequence 5 in Texas are somewhat problematic. The base has not been identified clearly but may be near the 1300 ft (396.2 m) level in the Threadgill Creek section. Strata near the top of Sequence 5 are partly obscured by travertine deposits in this section. The top of Sequence 5 is well exposed farther upstream along Threadgill Creek, in the Lange Ranch section.

Sequence 5 is a depositional cycle that includes lowstand deposits at the base, a transgressive to highstand portion in the middle, and lowstand deposits of Sequence 6 overlie it. Sequence 5 began with relative sea-level rise above a basal truncation surface (Fig. 32). As parts of the craton remained exposed, continued rapid subsidence on the miogeocline apparently provided accommodation for deposition of the Red Tops Lowstand. Sedimentation during this interval kept pace with the slow rate of accommodation, resulting in high-energy sediments. Lime mudstones of the overlying Lava Dam Member record lower-energy conditions due to more rapid rate of relative rise sea-level rise and increased accommodation. Strata of the lower Lava Dam Member appear to consist of numerous meter-scale cycles similar to those in the Hellnmaria Member. We subdivide Sequence 5 into three packages.

Package 5A—Lower Part of Red Tops Lowstand

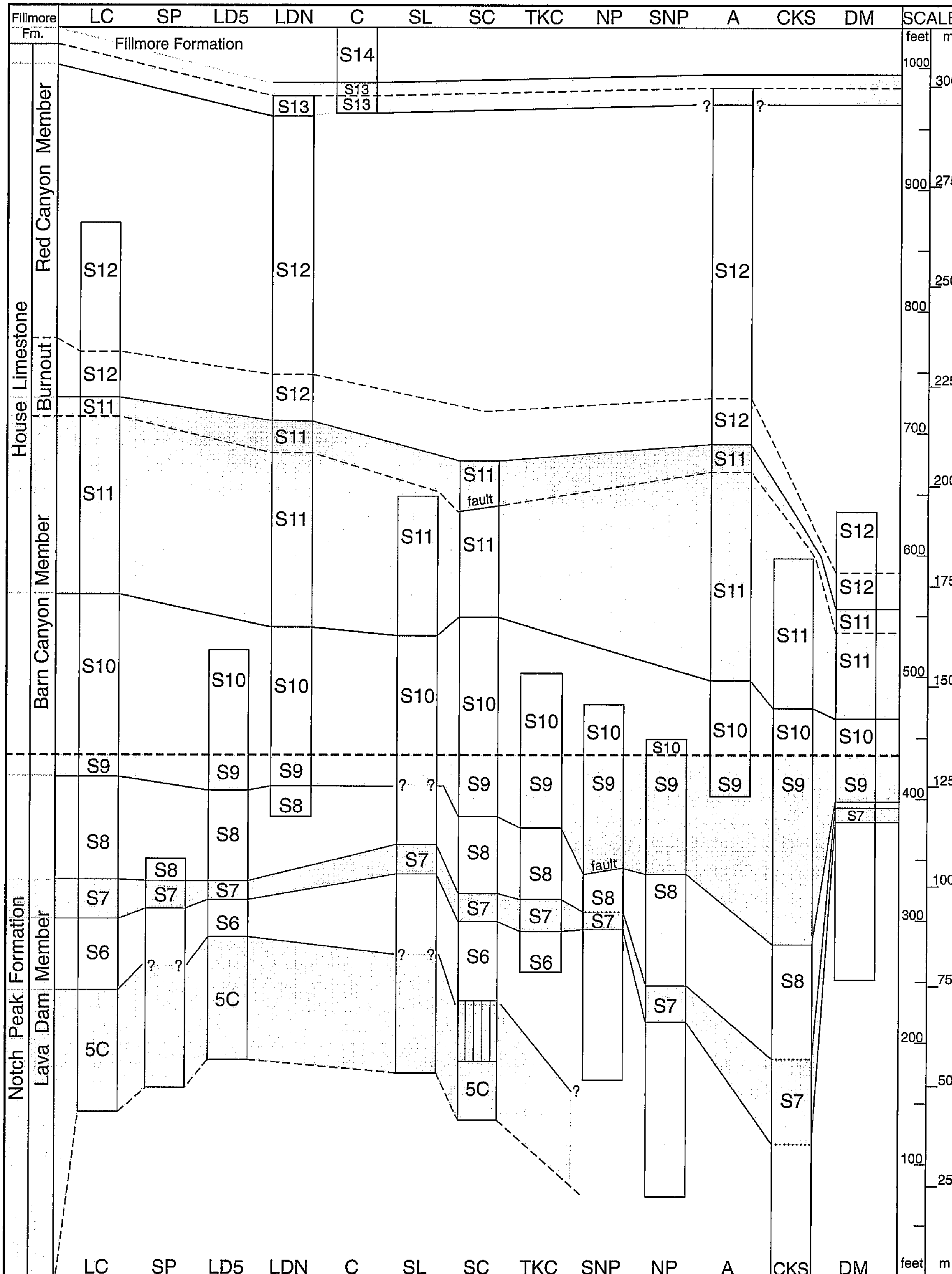
Package 5A includes the lowest part of the Red Tops Member, from the basal truncation surface to the base of a widespread stromatolite unit in the lower to middle Red Tops. Russell Shapiro (personal communication) studied stromatolites in the Red Tops at Lawson Cove and considers the base (rather than the top) of the stromatolite unit to record the low point of sea level within the Red Tops Lowstand. At Lawson Cove, Package 5A is only 17 ft (5.2 m) thick; thicknesses in other sections are shown in Table 23 and on Figure 19. The Red Tops is too poorly exposed at the Drum Mountains section to subdivide it.

Two conodont zones characterize Package 5A, and the stratigraphic relationships of these zones are especially clear at Steamboat Pass. Based on collections made after the report of Hintze et al. (1988), the lower 7 ft (2.1 m) of brown Red Tops strata are assigned to the *Proconodontus muelleri* Zone. The upper part of Package 5A is assigned to the *Eoconodontus notchpeakensis* Subzone of the *Eoconodontus* Zone. Trilobite data are sparse in this interval but suggest assignment to the *Saukiella junia* Subzone of the *Saukia* Zone.

At Threadgill Creek, Texas the base of Package 5A is probably near 1300 ft in the section. There is no clear top, but in the interval 1308–1320 ft (398.7–402.3 m) is a recessive unit of exceptionally glauconitic ooid grainstone to greensand with detrital quartz. Poor exposure of these soft strata precludes recognizing such features as truncation surfaces, but we infer that these strata represent the low point of the Red Tops Lowstand. Strata in this interval are referred to the *E. notchpeakensis* Subzone and to the *Saukiella junia* Subzone.

Package 5A appears to record a small transgressive-regressive cycle. Utah strata have a basal truncation surface that developed during a relative sea-level fall. The subsequent marine flooding provided accommodation for shallow-water carbonate deposition. The upper part of the package apparently records a time of reduced accommodation.

The insoluble residues from Package 5A have up to 82 per mil of quartz sand at Sneakover Pass (Fig. 16; Table 12). Four samples from the lower 14 ft (4.3 m) of the Red Tops at Steamboat Pass have values ranging from 20–67 per mil


Fillmore Fm.
LC SP LD5 LDN C SL SC TKC NP SNP A CKS DM
SCALE
Fillmore Formation
House Limestone
Red Canyon Member
Burnout
Barn Canyon Member
Notch Peak Formation
Lava Dam Member
S14
S13
S12
S11
S10
S9
S8
S7
S6
5C
fault
?
feet m
1000 900 800 700 600 500 400 300 200 100 0
300 275 250 225 200 175 150 125 100 75 50 25 0
LC SP LD5 LDN C SL SC TKC SNP NP A CKS DM

and include some silicified ooids. Two insoluble residues from Package 5A at Lawson Cove (Fig. 17, Table 13) have relatively high values of 16 and 21 per mil.

Package 5B—Upper Part of Red Tops Lowstand

Package 5B is the middle part of Sequence 5 and the upper part of the Red Tops Lowstand; this package includes the upper part of the Red Tops Member. The base of Package 5B is at a regression recorded in the Red Tops Member at the base of a widespread stromatolite unit. Stromatolites occur in the Red Tops at Steamboat Pass, Sevier Lake Corral North (Fig. 33), and Notch Peak. The Red Tops at Chalk Knolls has several stromatolite units, and we are unsure which to choose as the base of Package 5B. At Chalk Knolls South the base of Package 5B may be at the base of unit 14. Stromatolites are absent at Lava Dam Five, but unit 2 of the described section is a 5 ft (1.5 m) interval of glauconitic limestone, shale stringers, and halite that we interpret as the low point of the regression. At Sneakover Pass a thin covered interval is at the position of the stromatolite bed, which can be correlated to Notch Peak by an overlying key bed containing large lingulid brachiopods. The top of Package 5B is at a relative rise in sea level at the contact between the Red Tops and Lava Dam members. This horizon marks the top of the Red Tops Lowstand, and it is conformable where it is exposed.

Like Package 5A, the insoluble residue content of these strata is rather high, although we have data only from Lawson Cove (Table 13, Fig. 17). The insoluble residues of these samples contain abundant silicified ooids that are stained red by iron oxides; the red to brown color is typical for strata of the Red Tops Member.

Figure 31. Correlation of Package 5C and Sequences 6–14 (S6–S14) in Lava Dam Member of Notch Peak Formation, House Limestone, and lowest beds of Fillmore Formation. Odd-numbered sequences are shaded. Datum is Notch Peak-House contact. Sections at Lawson Cove (LC), Steamboat Pass (SP), Lava Dam Five (LD5), Lava Dam North (LDN), 1965 C section (C), and Sevier Lake (SL) are located on Wah Wah Arch. Sections at Sevier Lake Corral (SC), Tank Canyon (TKC), and Notch Peak (NP) are located in a transition zone between Wah Wah Arch and House Range Embayment. Sections at Sneakover Pass (SNP), Section A (A), and Chalk Knolls South (CKS) are located in House Range Embayment. Drum Mountains section (DM) is located on south flank of the Tooele Arch. For section locations, see Figure 1. Vertically ruled area at SC is a thick covered interval that may conceal boundary between Sequences 5 and 6. That boundary cannot be identified farther north and Package 5C merges with Sequence 6. Base of S7 at CKS is approximated by base of Cordylodus proavus *Zone; top of S7 at CKS and NP is approximated by base of* Fryxellodontus inornatus *Subzone.*

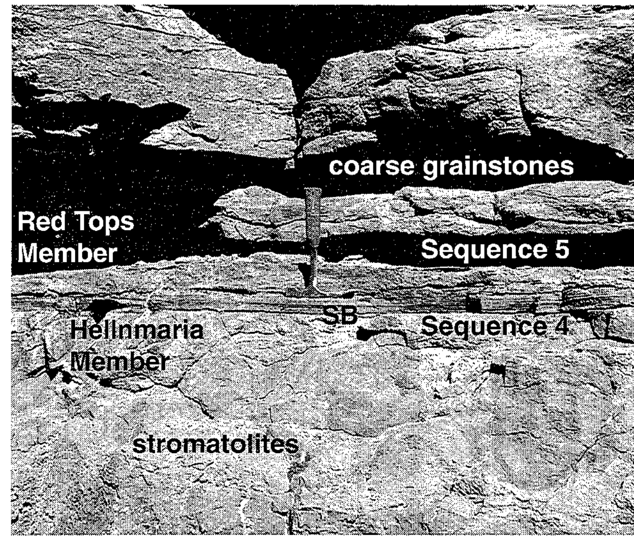


Figure 32. Boundary between Sequences 4 and 5 at Sneakover Pass section, central House Range. Stromatolites at top of Hellnmaria Member (top of Sequence 4) are truncated by planar Sequence Boundary (SB). Overlying grainstones (partly hidden in shadows) are at base of Sequence 5 and of Red Tops Member. Hammer for scale is 11 inches (28 cm) tall.

Strata of Package 5B are assigned to two conodont subzones, and the relationships are clearest at Steamboat Pass because of good exposure. Of the 38 ft (11.6 m) of Package 5B at Steamboat Pass, the lower 27 ft (8.2 m) are assigned to the *Eoconodontus notchpeakensis* Subzone, and the upper 11 ft (3.4 m) are assigned to the *Cambrooistodus minutus* Subzone. A similar relationship is at Lawson Cove, where the highest exposed bed of the Red Tops is the base of the *C. minutus* Subzone and overlying beds are covered. Package 5B at Steamboat Pass has trilobites assigned to the *Saukiella junia* Subzone of the *Saukia* Zone (Hintze et al., 1988, Fig. 4). The exact position of the base of the overlying *S. serotina* Subzone is unclear in Ibex sections. The top of Package 5B is probably close to the base of the subzone but may be above or below the subzone boundary.

The boundaries of Package 5B are difficult to recognize in Texas. The base of the package is probably in poorly exposed glauconitic strata. It is difficult to correlate the top of the Red Tops Lowstand to Texas because strata above the glauconitic interval are mostly high-energy grainstones that can not be compared to the low-energy lime mudstones of Package 5C (Lava Dam Member) in Utah. However, insoluble residue data (Table 21, Fig. 14) suggest that the top of Package 5B is ca. 24 ft (7.3 m) above the base of the Lange Ranch section, in the lower *Cambrooistodus minutus* Subzone, a level that is in the *Saukiella serotina* Subzone.

Figure 33. Southward view of Sevier Lake Corral North section in southern House Range showing sequence stratigraphic units. Base of section is in middle of Red Tops Member, in Package 5A. 1 = stromatolite unit, base of Package 5B. 2 = base of Package 5C, 31 ft (9.4 m) above base of section. Upper part of Package 5C and lower part of Sequence 6 are covered. 3 = base of Sequence 7; 4 = top of Sequence 7. Lower part of Sequence 8 is partly covered, upper part is in cliffs. 5 = base of Package 9A. Strata below 2 are part of Red Tops Member; strata above 2 are Lava Dam Member. Chevrolet S-10 Blazer with white luggage carrier shows scale.

Package 5B began at the peak of the Red Tops regression. Stromatolites at the base of Package 5B record the start of a relative rise of sea level and increasing accommodation. The rest of the package formed during a time when the rate of high-energy sedimentation kept pace with the slow rate at which accommodation was produced, so lowstand conditions persisted for some time. Overlying strata of the next package represent a time of transgression and more rapidly increasing accommodation.

Package 5B can be correlated from Lawson Cove to the Black Mountain section in Australia by using the carbon-isotope profiles published by Ripperdan and Miller (1995, Fig. 3). Near the bases of the two isotope profiles is the largest negative carbon isotope excursion that is present in each section, and the excursion peaks provide a basis for correlation between the sections. Ripperdan (2002) named this very distinctive excursion the HERB Event. At Lawson Cove this event occurs less than one meter above the top of the stromatolite interval within the Red Tops Member, at sample LCL-RT17. This event is thus only slightly above the base of Package 5B, and the interval through which the isotope values were dropping is within Package 5A and the lowest part of Package 5B. At Black Mountain the HERB Event occurs at the base of conodont assemblage 3, the *Hispidodontus appressus* Zone (Shergold and Nicoll, 1992, Fig. 2, p. 85). *H. appressus* Nicoll does not occur in North America, so a direct biostratigraphic correlation is not possible. However, a correlation can be based on the relative position of the HERB Event within the conodont succession. At Black Mountain, the HERB Event peak is between the lowest occurrences of *Eoconodontus notchpeakensis* (Australian assemblage 2) and *Cambrooistodus minutus* (Australian assemblage 4), which is the relative position of the HERB Event at Lawson Cove. At Black Mountain the carbon isotope peak is at the base of the Ninmaroo Formation and immediately above the Lily Creek Member of the Chatsworth Limestone. The Lily Creek is sandstone that has been interpreted as eolian in origin, and it can be correlated with the lower part of the Red Tops Member at Lawson Cove, within and below the stromatolitic interval. We interpret this sandstone as recording a relative sea-level fall that resulted in subaerial exposure of the cratonic Georgina Basin in Australia; this sea-level fall is correlated with a similar event during deposition of Package 5A in Utah. The fossiliferous carbonates at the base of the overlying Ninmaroo Formation record the succeeding rise in sea level and correlate with the part of the Red Tops that overlies the stromatolites of Package 5B.

Package 5C—Deepening

The remainder of Sequence 5 includes a little less than the lower half of the Lava Dam Member of the Notch Peak Formation and constitutes Package 5C. The dominant lithology is gray lime mudstone to wackestone with minor lenses of grainstone, packstone, and intraclast conglomerate. If it is well exposed, the contact with underlying strata of Package 5B is quite sharp; at Sevier Lake Corral this contact records a rapid rise in sea level (Fig. 33) and a change from lime grainstone to lime mudstone. We interpret the lower Lava Dam as representing the transgressive and highstand parts of Sequence 5. These strata are 105 ft (32.0 m) thick at Lawson Cove (Tables 13, 23) and include units 7–10; at Steamboat Pass Package 5C includes described units 29–34 and part of unit 35; Package 5C is 90 ft (27.4 m) thick at Lava Dam Five and includes described units 21–32. At Sevier Lake, Sneakover Pass, Notch Peak, and Chalk Knolls South, Package 5C is not separable from Sequence 6 because strata of Package 6A are nonresistant lithologies that typically are poorly exposed; this boundary is probably in a covered interval at Sevier Lake Corral North (Fig. 33). Packages 5C and 6B are dominantly lime mudstones that together comprise the Millardan part of the Lava Dam Member. Above the top of Package 5C is at a thin interval of lowstand strata that are pink intraclast conglomerate at Lawson Cove. In Texas it is difficult to distinguish Package 5B from 5C, but the top of 5C is a sharp truncation surface.

Package 5C comprises a little more than the lower half of the *Cambrooistodus minutus* Subzone of the *Eoconodontus* Zone and the *Saukiella serotina* Subzone of the *Saukia* Zone.

At Lawson Cove and other Utah sections, Package 5C includes many small meter-scale cycles that are expressed on outcrop as thin covered slopes overlain by ledges of lime mudstone to skeletal wackestone. Along strike the top few centimeters of such ledges may include a thin lens of skeletal and intraclast packstone to grainstone that is the base of the overlying little cycle. The concentration of quartz sand in Package 5C is quite low except for a sharp increase at the top, where there is a transition to the overlying lowstand strata of Package 6A (Fig. 17). We interpret these strata as representing a moderately deep subtidal environment deposited during a period when sea level was rising and accommodation was increasing.

SEQUENCE 6

Sequence 6 is bounded by truncations on the Texas craton, by lowstand deposits on the Wah Wah Arch, and by intervals that record facies shifts within subtidal strata in the House Range Embayment. Thus, it is an example of a sequence bounded by unconformities and by laterally correlative conformity. Sequence 6 is in the middle part of the Lava Dam Member; it is only 54.5 ft (16.6 m) thick at Lawson Cove and 38 ft (11.6 m) thick at Lava Dam Five.

Sequence 6 conodont faunas are assigned to the upper part of the *Cambrooistodus minutus* Subzone of the *Eoconodontus* Zone and to the lowest part of the *Hirsutodontus hirsutus* Subzone of the *Cordylodus proavus* Zone; trilobite faunas are assigned to the upper part of the *Saukiella serotina* Subzone of the *Saukia* Zone and to the base of the *Eurekia apopsis* Zone. The top of Sequence 6 is slightly above the base of the Ibexian Series. We divide Sequence 6 into three packages.

Package 6A—Abrupt Shallowing

At Lawson Cove Package 6A is a thin interval of lowstand strata that is 10 ft (3.0 m) thick and includes two conodont samples that have relatively high concentrations of quartz sand (Fig. 17). The highest sample of Package 5C is lime mudstone to wackestone that has even higher sand content. The two samples of Package 6A are pink skeletal to intraclast and flat-pebble conglomerate and have successively less sand, but they are a typical lowstand lithology. Above these beds is a covered interval that may conceal additional strata with abundant siliciclastic material. At Steamboat Pass Package 6A apparently occurs in a poorly exposed interval in the upper part of unit 35. The package is 9 ft (3.7 m) thick at Lava Dam Five and includes units 33–36. Those strata include lime mudstone, intraclast and flat-pebble conglomerate, and very thin bedded, strongly burrowed, very argillaceous lime mudstone. The quartz sand content of this interval is unknown. We interpret this thin interval of strata as representing a brief drop in relative sea level or decrease in accommodation with an attendant influx of siliciclastic sediment. It is not possible to separate Sequence 6 from Package 5C in sections north of Lava Dam Five because lowstand deposits at the base of the sequence are either not exposed or have changed facies.

In the Lange Ranch section, Texas there is a conspicuous truncation surface at the top of sample LR 45.25 (Table 21), which is 13.25 ft (4.0 m) below the top of the *Cambrooistodus minutus* Subzone (Fig. 34). A sample from 3.25 ft (1.0 m) below the truncation has high insoluble residue compared with adjacent samples (Fig. 14) and is comparable to the top sample of Package 5C at Lawson Cove. We interpret the increase in quartz sand as indicating a minor regression, which culminated slightly higher in subaerial exposure and truncation. Consequently, Package 6A is probably missing in Texas and is represented by hiatus at the truncation surface.

At about the stratigraphic level of this sandy interval in the Ibex area, it is common to find a few thin beds of lime mudstone with silicified trilobites such as *Eurekia, Euptychaspis* (Hintze, 1951, p. 33; Hintze et al., 1988, p. 24, unit 36), and other taxa characteristic of the *Saukiella serotina* Subzone. Diagenetic silicification of these fossils probably is related to the availability of silica from siliciclastic sediment in adjacent beds.

Package 6B—Deepening

Strata of Package 6B are mostly lime mudstone to trilobite wackestone, much of it lacking chert. The interval consists of several meter-scale cycles that are similar to strata in the upper part of Sequence 5. Package 6B is 38 ft (11.6 m) thick at Lawson Cove and includes units 13–17. At Steamboat Pass, Package 6B probably includes described units 36–44; these strata are 29 ft (8.8 m) thick at Lava Dam Five and include units 37–42. The top beds of Package 6B have slightly more quartz sand than underlying strata (Fig. 17), and this interval corresponds to the interval that is cherty. This increase in sand is part of the general increase in siliciclastic content that continues into Sequence 7. We attribute this increase to the onset of relative sea-level lowering, erosion in the source areas, and transport of the resulting siliciclastic material into the Ibex area. Package 6B is in the upper part of the *Cambrooistodus minutus* Subzone and the *Saukiella serotina* Subzone. In the Lange

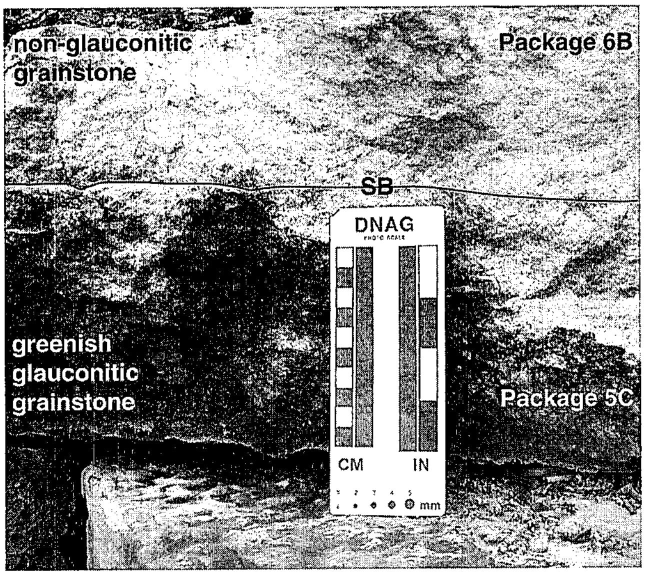


Figure 34. Truncation surface forms sequence boundary (SB) between Packages 5C and 6B in San Saba Member of Wilberns Formation, Llano uplift, Texas. SB is at 45.25 foot-level in Lange Ranch section and is emphasized with black line.

Ranch section, Texas, the base and the top of the sequence are truncation surfaces that bound an interval that is 13.25 ft (4.0 m) thick.

Package 6C—Shallowing to Near Exposure

Package 6C is the thinnest of the three packages of Sequence 6. The base of Package 6C is at the first indication of regression above the lime mudstones of Package 6B; this horizon coincides with the base of the *Cordylodus proavus* Zone and of the Ibexian Series. The top of the package is the base of the Tank Canyon Bed, a thin ooid grainstone that we interpret as marking a regressive low point. Package 6C ranges from 6.5 ft (1.8 m) thick at Lawson Cove to 1.5 ft (0.5 m) at Sevier Lake Corral and Tank Canyon (Table 23). Package 6C cannot be recognized at Chalk Knolls South because the Tank Canyon Bed is not present in this part of the House Range Embayment. Figure 31 shows the top of combined Sequences 5 and 6 as a dashed line at Chalk Knolls South. That line is a proxy for the top of Sequence 6 and is placed at the base of the *Cordylodus proavus* Zone, which is usually slightly below the top of Sequence 6.

At Lawson Cove, rocks at the base of Package 6C record a lithologic change from lime mudstone to very argillaceous lime mudstone with minor intraclast grainstone. This upper part of Sequence 6 is argillaceous and silty, and it is a covered interval in sections throughout the Ibex area, so it has been exposed by digging at most sections (Miller et al., 2001, Fig. 7). Commonly, the lowest natural exposure of the Ibexian Series is the Tank Canyon Bed, a thin ooid, peloid, skeletal, and intraclast grainstone that is the base of the next sequence. Package 6C records an increase in depositional energy and shallowing from subtidal lime mudstone to shallow subtidal grainstone at the base of the Tank Canyon Bed. Because our insoluble residue data (Table 13, Fig. 17) reflects the sand fraction, the argillaceous and silty material are not recorded as a deflection in the insoluble residue plots.

The base of Package 6C is associated with the major faunal turnover that characterizes the base of the Ibexian Series. At Lawson Cove a single sample, LCL-LD158 (Table 4), has the highest occurrence of several conodont species that are diagnostic of the *Eoconodontus* Zone and also has the lowest occurrence of *Cordylodus andresi,* which characterizes the base of the *C. proavus* Zone and the base of the Ibexian Series (Fig. 6). This sample is from the bed at the base of Package 6C. Several abundant conodont taxa that occur through Sequence 4 to Package 6B are not found above this sample. The next bed is unusually dark lime mudstone to wackestone. This bed and overlying very argillaceous beds yielded only unidentifiable fragments of conodonts. The two samples from this interval are the only limestones in the Lawson Cove section to be essentially barren of conodonts. Through the next 4.5 ft (1.4 m) of strata, the abundance of *Cordylodus andresi* increases steadily, and other conodont taxa occur for the first time, indicating recovery of the conodont fauna following a major faunal crisis and extinction.

The 4.5 ft interval of recovery of the conodont fauna coincides with an interval having few trilobites. The highest occurrence of *Eoconodontus* Zone conodonts is also the highest occurrence of *Saukiella serotina* Subzone trilobites. Trilobites diagnostic of the *Eurekia apopsis* Zone occur within this conodont recovery interval, but in only one sample (Table 4). Trilobites are more abundant through Package 6C at Lava Dam Five; the ranges of conodonts and trilobites in that part of the section were documented in detail by Ross et al. (1997, Fig. 8). Package 6C is represented by similar but thinner stratigraphic and faunal successions at Steamboat Pass and Lava Dam Five. The base of Package 6C at Sevier Lake Corral is an iron-rich horizon marked by clusters of iron-oxide pseudomorphs after pyrite (Fig. 35). This surface is 1.5 ft (0.5 m) below the Tank Canyon Bed. The surface also coincides exactly with the faunal change between the *Eoconodontus* Zone (below the surface) and the *Cordylodus proavus* Zone (above the surface). We interpret this surface at the base of Package 6C as marking a shift to reducing conditions that perhaps is associated with a global anoxic event (Wright et al., 1987).

This horizon is at the level of an unusually dark, unfossiliferous limestone bed at Lawson Cove (samples LCL-LD158.2 to 158.5).

The irregular distribution of strata in Package 6C both regionally and across most of North America is related to erosion at the base of Sequence 7. At Sneakover Pass a truncation surface occurs about 6 inches (15 cm) above the base of the *C. proavus* Zone, at the base of the Tank Canyon Bed (Miller et al., 2001, Fig. 8). This is the only truncation surface we have observed at this stratigraphic level in the Ibex area. A planar truncation surface at the base of the *C. proavus* Zone in the Whipple Cave Formation in the Egan Range, Nevada can be traced for 200 m or more along strike (Miller, 1984). At Lange Ranch in Texas, the base of the *C. proavus* Zone is clearly a subaerial exposure surface, illustrated in Figure 36 (see Miller, 1992 for further discussion). The Nevada and Texas exposure surfaces record the time of Package 6C as a hiatus rather than an interval of strata.

This thin interval of strata, Package 6C, records the first stage in a period of low sea level that we refer to as the Lange Ranch Lowstand. Most of this lowstand is part of Sequence 7, and it is discussed below.

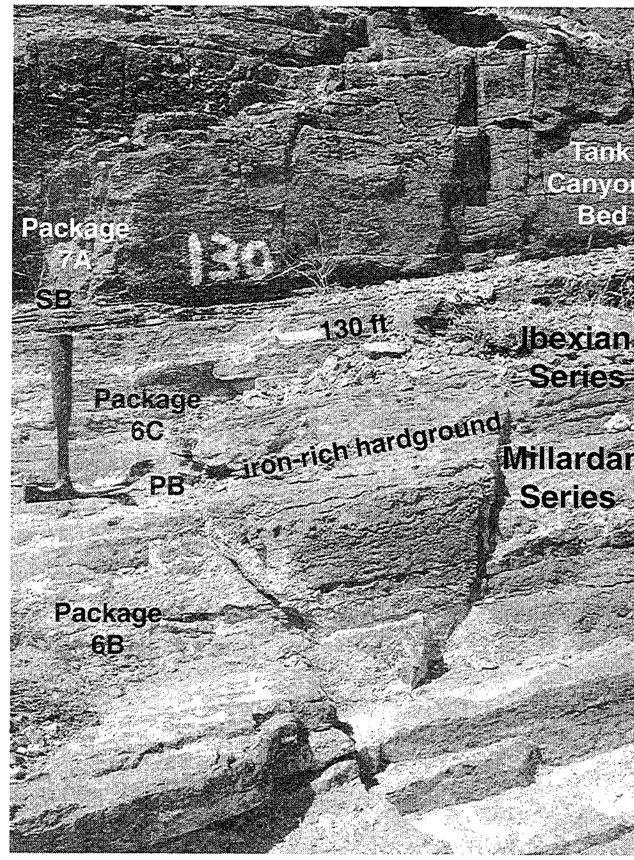


Figure 35. Top of Sequence 6 and lower part of Sequence 7 at Sevier Lake Corral North section, southern House Range. PB = Package Boundary between Packages 6B and 6C (boundary between Millardan Series and Ibexian Series), at128 ft in described section (CD-ROM), located at head of hammer. Iron-rich hardground and clusters of hematite pseudomorphs after pyrite occur along this package boundary. SB = base of Sequence 7. Hammer is 11 inches (28 cm) tall.

IBEXIAN SEQUENCES

Sequences 7–14 comprise the bulk of the lower part of the Ibexian Series, although Package 6C marks the base of the series. This interval includes five named lowstands and the Stonehenge Transgression. These strata include the top of a large sequence recognized by Osleger and Read (1993), as well as two large sequences recognized by Ross and Ross (1995) and the base of a third (Fig. 15).

SEQUENCE 7—LANGE RANCH LOWSTAND

Sequence 7 is a thin interval near the middle of the Lava Dam Member, but it includes three distinct packages that decrease in thickness upward and have increasing siliciclastic content. The interval records a general upward-shallowing trend that ends with subaerial exposure at the top of the sequence. Sequence 7 extends from the base of the Tank Canyon Bed to the top of the Lawson Cove Bed, and it ranges in thickness from 31.5 ft (9.6 m) at Lawson Cove to 15.5 ft (4.7 m) at Lava Dam Five (Table 23, Fig. 31). The thickness is uncertain at Notch Peak and Chalk Knolls South because the top of the sequence (top of Lawson Cove Bed) can not be identified, but it is a minimum of 72 ft (21.9 m) thick at Chalk Knolls South in the House Range Embayment. Sequence 7 is missing entirely in the Drum Mountains, where there is an unconformity at this level.

Sequence 7 is only 11.5 ft (3.5 m) thick at the Lange Ranch section, Texas, and it includes three hiatuses. These Texas and Utah strata record the Lange Ranch Eustatic Event of Miller (1984, 1992, 1995) and other authors. Strata deposited during this time were described by Miller (1984, 1992) as consisting of two thin packages, but it is now clear that the second of the three packages present in Utah sections is missing entirely at the Lange Ranch section. Herein, we note a change in the conceptual model for the history of sea level and refer to this interval as the Lange Ranch Lowstand. Nevertheless, one or more of the abrupt regressive events marking the bases of packages in Sequence 7 may be recorded as discrete sequence boundaries elsewhere. Discussion of these "eustatic events" were early attempts to apply sequence stratigraphic concepts, constrained by detailed biostratigraphy, on the scale of outcrops.

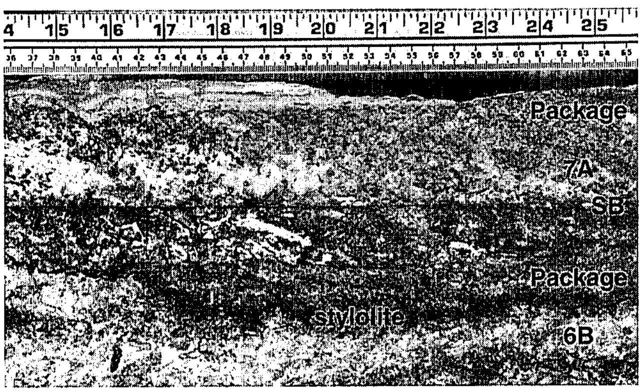


*Figure 36. Polished slab of San Saba Member of Wilberns Formation, at 58.5-foot level in Lange Ranch section, Texas. Truncation surface at sequence boundary (SB) separates Package 6B (*Saukiella serotina *Subzone and* Cambrooistodus minutus *Subzone) from Package 7A (*Eurekia apopsis *Zone and* Hirsutodontus hirsutus *Subzone). Package 6C is missing at sequence boundary and conodonts from top bed of Package 6B are weathered due to subaerial exposure. Scale in inches and cm.*

Package 7A—Lower Lange Ranch Lowstand

Package 7A is the thickest of the three packages in Sequence 7 and comprises strata from the base of the Tank Canyon Bed to an abrupt increase in quartz sand content at the base of the next package. The base of Package 7A is conformable in the Ibex area except perhaps at Sneakover Pass, where a ferruginous hardground marks the base of the Tank Canyon Bed (Miller et al., 2001, Fig. 8). The top of the package is characterized by the lowest occurrence of the conodont *Cordylodus proavus* and the trilobite *Plethopeltis arbucklensis,* which marks the base of the *Missisquoia* Zone and of the Canadian Series. The lowest occurrence of the brachiopod *Eurytreta sublata* is only 1 ft (0.3 m) higher at Lawson Cove. Package 7A varies in thickness from 17.5 ft (5.3 m) at Lawson Cove to 8 ft (2.4 m) at Sneakover Pass. The thickness recorded in Table 23 may not be accurate for Steamboat Pass, Sevier Lake, and Sneakover Pass due to inadequate density of sampling. The thickness of Package 7A cannot be determined at Notch Peak and Chalk Knolls South because the base or top of the package cannot be identified.

Insoluble residues are useful to delineate Package 7A. At Lawson Cove the grainstone bed below the Tank Canyon Bed (sample LCL-LD164 in Table 9) records an influx of quartz sand, indicating shallowing conditions. The quartz sand content is diminished in overlying strata, indicating deeper conditions (Fig. 17). The upper beds of Package 7A are mixed mudstone-packstone-grainstone, but typically they form a prominent cliff, above which is a thin covered interval (Fig. 37). The upper ledge-forming part of Package 7A represents slightly deeper conditions, but accommodation was filled near the top of the package. The top of the package, at sample LDL-LC181 (Table 13), has slightly higher quartz sand content and is transitional with the next package, which records a large influx of quartz sand.

The contact between Packages 7A and 7B is completely exposed on a cliff near the Tank Canyon section. The top of Package 7A has megaripples overlain by 6 in (15 cm) of thin-bedded limestones that end at a planar truncation surface. This truncation is interpreted as the top of Package 7A and as recording brief subaerial exposure due to loss of accommodation. The megaripples are exposed at Lawson Cove, but a thin covered interval obscures the overlying thin beds there and at other sections.

The top of Package 7A coincides with the lowest occurrence of *Cordylodus proavus.* The top of the package is also the top of the *Eurekia apopsis* Zone at Lava Dam Five, where trilobite collections are more closely spaced than at Lawson Cove (Ross et al., 1997). In the Lange Ranch section in Texas, Package 7A includes the *Hirsutodontus hirsutus* Subzone and the *Eurekia apopsis* Zone, an interval that is 11.5 ft (3.5 m) thick.

Package 7B—Middle Lange Ranch Lowstand

Package 7B is thinner than 7A but thicker than 7C (Fig. 17). Package 7B ranges in thickness from 9 ft (2.7 m) at Lawson Cove to 3 ft (0.9 m) at Tank Canyon (Table 23). The thickness of Package 7B cannot be determined accurately at Steamboat Pass, Sevier Lake, Sneakover Pass, and Notch Peak because sampling intervals were too large. Boundaries between Packages 7A–7C are indistinguishable at Chalk Knolls South because of facies changes that occur as these strata are traced into the House Range Embayment.

At Lawson Cove the base of Package 7B contains nearly 100 per mil quartz sand (Table 13, Fig. 17), which we interpret as indicating a sudden drop in sea level that resulted in nearshore siliciclastics prograding into the area. The concentration of sand decreases upward through the next several samples and then increases abruptly near the top of the package. We interpret this cyclic change as recording a relative rise in sea level followed by filling of accommodation.

Near the Tank Canyon section, the top of Package 7A is a planar truncation surface, noted above. The lowest beds of Package 7B are thin, recessive limestones and evaporites that we interpret as a sabkha (supratidal) facies that formed during the initial transgression following the subaerial exposure recorded by the truncation surface. These beds are obscured by a thin covered interval at Lawson Cove and other sections.

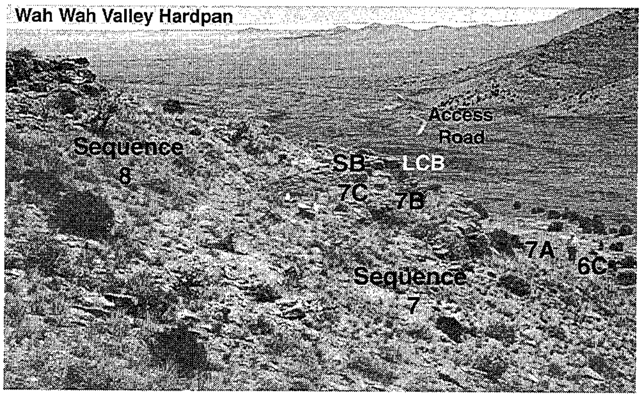


Figure 37. Sequence 7 in lower segment of Lawson Cove section, northern Wah Wah Mountains. J. F. Miller stands at base of Package 6C (= 6C), base of Ibexian Series. 7A = base of Package 7A, base of Tank Canyon Bed. 7B = base of Package 7B, base of Canadian Series. 7C = base of Package 7C. LCB = Lawson Cove Bed. SB = sequence boundary at base of Sequence 8, base of flat-pebble conglomerate above Lawson Cove Bed (see Figure 40).

Package 7B comprises the upper part of the *Hirsutodontus hirsutus* Subzone that is characterized by the presence of *Cordylodus proavus,* and the top of Package 7B is at the base of the next conodont subzone. Package 7B nearly coincides with the *Missisquoia depressa* Subzone (Fig. 3), although definition of the stratigraphic package and the subzone are based on different criteria. The top of the trilobite subzone is 2 ft (0.6 m) above the top of the package. This 2-ft interval includes a white chert marker bed that yielded conodonts but no trilobites (Fig. 38).

The base of Package 7B coincides with the base of the Canadian Series of Stitt (1977), an important interval of faunal turnover among conodonts, organophosphatic brachiopods, and trilobites. The conodont change is the lowest occurrence of *Cordylodus proavus.* The lowest occurrence of the brachiopod *Eurytreta* Rowell is in sample LCL-LD183, only 1 ft (0.3 m) above the base of the package. *Eurytreta sublata* Koneva and Popov, the oldest species of the genus, begins at this level and occurs through the rest of Sequence 7 and all of Sequence 8 (Fig. 4). Figures 6, 8, and 10 indicate that a succession of species of this genus occur in Skullrockian strata at Lawson Cove and Lava Dam North, and it occurs also in Sequence 14. The trilobite faunal change is the boundary between the Ptychaspid and Symphysurinid Biomeres. This horizon marks the disappearance of numerous trilobite taxa, including species, genera, and families.

At Lange Ranch, Texas all of Package 7B, the *Missisquoia depressa* Subzone, is missing, and the overlying *M. typicalis* Subzone rests unconformably on the *Eurekia apopsis* Zone (Taylor, 1984; Miller, 1992, Fig. 3), as illustrated on Figure 39. Taylor (1984) documented the presence of the *M. depressa* Subzone (Package 7B) in a thin interval at the Bluff Creek section, Texas (Miller, 1992, p. 400).

Package 7C—Upper Part of Lange Ranch Lowstand

Package 7C is the youngest package of Sequence 7 and typically is the thinnest, ranging in thickness from 10 ft (3.0 m) at Sneakover Pass to 2.5 ft (0.8 m) at Lava Dam Five and Sevier Lake Corral North (Table 23). Its thickness cannot be determined at Notch Peak and Chalk Knolls South because the key beds at the base or top of Package 7A have not been identified.

Package 7C has very distinctive lithology. The basal bed is a white to brown to black chert bed that is typically 4–6 in (10–15 cm) thick. It contains relict features indicative of cross-lamination. Sample LCL-LD191.2 was a slab cut vertically through a large block of this bed from Lawson Cove; it was taken from the place illustrated on Figure 38. Discontinuous areas of the slab dissolved in acetic acid, and the insoluble residue produced conodonts that included the lowest *Fryxellodontus inornatus* at Lawson Cove. The sample also produced insoluble residues of 29.9 per mil quartz sand (Table 9, Fig. 17), and this bed is interpreted as a very sandy carbonate (or perhaps calcareous sandstone) that has been recrystallized to chert. Above this marker bed is flat-pebble conglomerate with some edgewise clasts up to 2 in (5 cm) across, and this bed also contains abundant (33.7 per mil) quartz sand. This conglomerate grades laterally into grainstone that contains the lowest occurrences of the trilobite *Missisquoia typicalis* and the calcitic brachiopod *Apheoorthis.* This conglomerate formed a base for growth of stromatolites up to 4 ft (1.2 m) high in the overlying Lawson Cove Bed.

The boundary between Packages 7B and 7C is a planar truncation surface where it is well exposed in a cliff near the Tank Canyon section. We interpret this truncation as indicating brief subaerial exposure at the top of Package 7B. A bed of flat-pebble conglomerate only 1–2 in (2.5–5 cm) above this truncation has well rounded pebbles up to 3 in (8 cm) across. A white to brown chert bed occurs 2 ft (0.6 m) higher, below the Lawson Cove Bed. These litologies suggest shallow, high-energy conditions and an influx of quartz sand during deposition of Package 7C.

The top of Package 7C is at the top of the Lawson Cove Bed, which forms most of the package (Miller et al., 2001, Fig. 9). At Lawson Cove this bed has little quartz sand (Table 13, Fig. 17) except for one sample that yielded 35.5 per mil quartz in the form of authigenic, doubly terminated euhedral crystals. The top of the Lawson Cove Bed at Lawson Cove is a smooth, undulatory surface with large discoidal carbonate clasts perched on it (Fig. 40). These

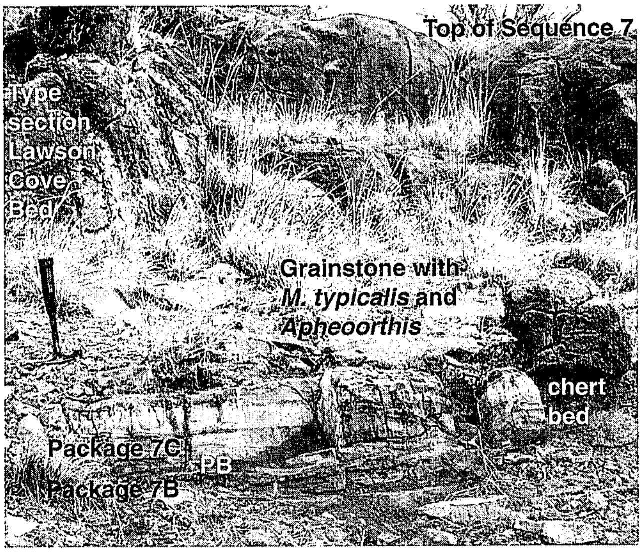


Figure 38. Package 7C in lower segment of Lawson Cove section, northern Wah Wah Mountains. PB = package boundary between Packages 7B and 7C. Base of Package 7C is white to brown chert marker bed at field number 191, middle of Package 7C is skeletal grainstone grading into flat-pebble conglomerate, top of Package 7C at field number 196 is top of stromatolitic Lawson Cove Bed. Chert bed is base of Fryxellodontus inornatus *Subzone; grainstone is base of* Missisquoia typicalis *Subzone. Hammer for scale is 11 inches (28 cm) tall. Compare with Figures 40–44.*

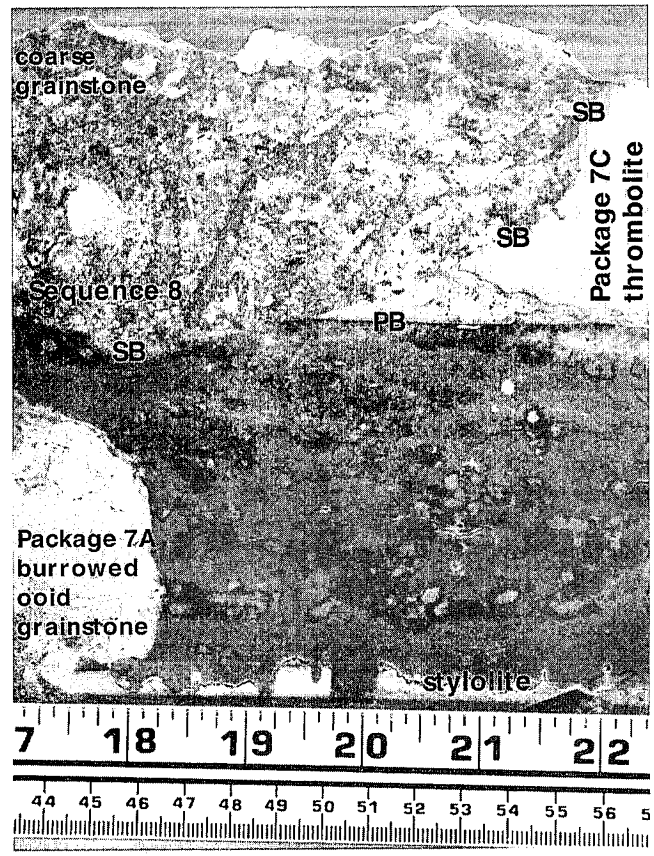


*Figure 39. Complex boundary between Sequences 7 and 8 in San Saba Member of Wilberns Formation, central Texas. PB = planar Package Boundary that separates Package 7A (*Eurekia apopsis *Zone) from small erosional remnant of Package 7C (*Fryxellodontus inornatus *Subzone and* Missisquoia typicalis *Subzone); Package 7B (*Missisquoia depressa *Subzone) is missing at this boundary. Package 7C is a small thrombolite on right growing on grainstone above letters "PB." Thrombolite and grainstone are truncated by inclined sequence boundary (= SB) that also truncates planar Package Boundary ca. 2 cm left of "PB" and cuts into Package 7A. Boundary occurs at 70 ft in Lange Ranch section. Scale in inches and cm. For another small erosional remnant a few meters along strike, see Miller (1992, Fig. 3). For outcrop photo, see Taylor (2000); this level is at knees of person in photo. Compare with Figures 38, 40–44.*

are part of a coarse flat-pebble conglomerate at the base of Sequence 8.

A distinctive succession of strata—chert, lower flat-pebble conglomerate, stromatolite, upper flat-pebble conglomerate (the latter considered part of Sequence 8)—is generally recognizable in sections from Lawson Cove northward to Sneakover Pass. Our interpretation of Package 7C is that the chert represents quartz-rich sediment that was deposited on a tidal flat during a regression (accommodation minimum) when the source area was exposed and abundant quartz sand was transported into the Ibex area. The lower flat-pebble conglomerate contains clasts of tidally laminated carbonates that became incorporated into a storm deposit. Development of a widespread stromatolitic bioherm indicates somewhat deeper but still peritidal conditions during a brief period of increasing accommodation. The undulatory top of the Lawson Cove Bed resulted from exposure and dissolution during a drop in sea level, but the original relief probably was reduced by abrasion during the subsequent rise in sea level. The upper flat-pebble conglomerate (base of Sequence 8) contains tidally laminated carbonate clasts and may have accumulated during the initial transgression following exposure.

Of the various sections that preserve Package 7C, the most interesting is Sevier Lake Corral (Fig. 33). There the top of the Lawson Cove Bed has several small grikes (karst dissolution cavities or pockets) that are filled with quartz sand that is stained dark brown (Figs. 41, 42). The top of the Lawson Cove Bed is capped by a discontinuous brown sandstone 1–2 cm thick. Along strike this sandstone outlines more than 1 ft (30 cm) of karst relief on the upper surface of the Lawson Cove Bed and fills grikes locally (left side of Fig. 41). The relief and grikes demonstrate that this bed was subaerially exposed and was subjected to dissolution during a sea-level lowstand. Quartz sand

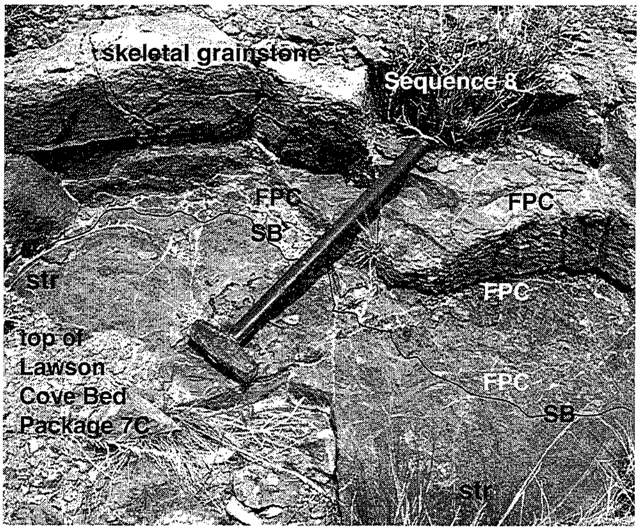


Figure 40. Oblique top view of sequence boundary (SB) between Package 7C and Sequence 8 at 196 ft in lower segment of Lawson Cove section. Flat-pebble conglomerate (FPC) and grainstone at base of Sequence 8 are cemented to stromatolites(str) along irregular top of Lawson Cove Bed. Head of sledge hammer is 6.25 inches (16 cm) across. Compare with Figures 41–44.

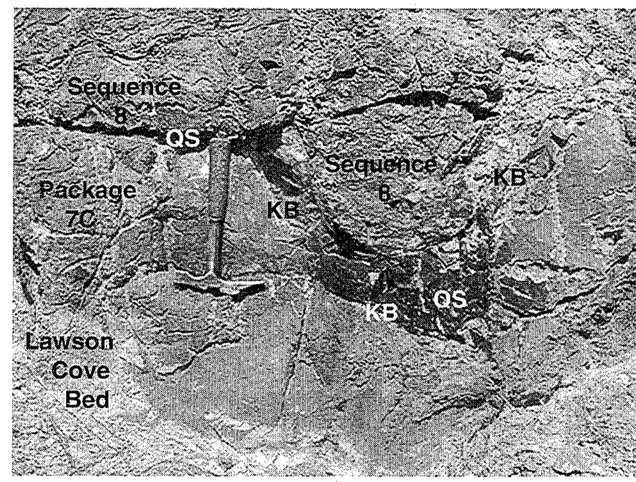


Figure 41. Karst sequence boundary (KB) between Package 7C and Sequence 8 at Sevier Lake Corral North section. Dark quartz sand (QS) fills dissolution cavity (grike) in upper part of Lawson Cove Bed in center of photo and covers top of Lawson Cove Bed to left of hammer handle; hammer is 11 inches (28 cm) tall. Quartz sand is base of Sequence 8, at 153 ft in described section (CD-ROM). Compare with Figures 40, 42–44. Figure 42 is ca. 50 ft (15 m) along strike to north, near location 4 on Figure 33.

was deposited subsequent to the dissolution. Abrasion during the subsequent transgression was not sufficient to erode away these karst features at this location but may have done so at other sections.

Evidence of exposure at the top of the Lawson Cove Bed can not be identified north of Sevier Lake Corral. This discrete bed is present at Tank Canyon and Sneakover Pass, which are located in the transition zone between the Wah Wah Arch and the House Range Embayment. At Notch Peak and Chalk Knolls South this bed is presumably just the base of a thick interval of stromatolites that kept up with accommodation in the rapidly subsiding House Range Embayment.

The brown sandstone at Sevier Lake Corral represents the highest concentration of quartz sand related to the three packages of Sequence 7. The base of Package 7A has an influx of quartz sand; the base of 7B is limestone with nearly 10 per cent quartz sand; the base of 7C is a chert bed that is a diagenetically recrystallized sandy carbonate; and the base of Sequence 8 has quartz sandstone in grikes. We interpret that the top of the Lange Ranch Lowstand represents the time of maximum regression during all of Sequence 7 (see Fig. 3). Each package formed during times of alternating increasing and decreasing accommodation. The entire lowstand shows an increase in sand and the successive thinning of Packages 7A–7C. The top of Package 7C is the top of Sequence 7 and the culmination of a relative sea-level fall.

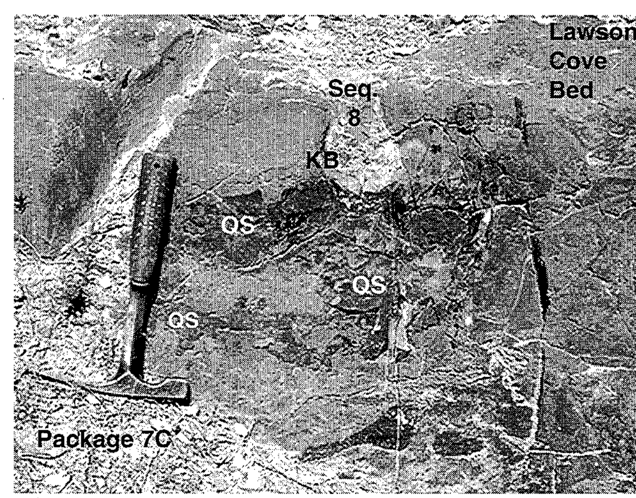


Figure 42. Karst sequence boundary (KB) between Package 7C and Sequence 8 at Sevier Lake Corral North section. Dark quartz sand (QS) fills dissolution cavity (grike) in upper part of Lawson Cove Bed in center of photo. Quartz sand is base of Sequence 8, at 153 ft in described section (CD-ROM). Compare with Figures 39–41, 43, 44. Figure 41 is ca. 50 ft (15 m) along strike to south, near location 4 on Figure 33.

Fluctuations of sea level associated with Sequence 7 (Fig. 3) apparently placed great stress on shallow marine faunas and resulted in considerable evolutionary change among them. The abrupt drop in sea level just below the sequence (Package 6C) coincided with a mass extinction among conodonts and trilobites, an event that characterizes the base of the Ibexian Series (Ross et al., 1997). A second sea-level drop at the base of Package 7B coincided with a second turnover among trilobites, the Ptychaspid-Symphysurinid Biomere boundary. This faunal change eventually was recognized as the base of the Canadian Series (Stitt, 1977; Miller, Loch et al., 1999). Conodonts were minimally affected at this level, but this horizon is characterized by the lowest occurrence of *Cordylodus proavus*. The base of Package 7C has the lowest occurrences of the conodont *Fryxellodontus inornatus*, the trilobite *Missisquoia typicalis*, and the brachiopod *Apheoorthis*.

It is curious that the fauna changes very little at the top of Sequence 7, which is at the culmination of a relative sea-level fall during this interval of protracted lowstand. One new conodont species, *Fryxellodontus* n. sp. aff. *F. lineatus* (Miller, 1969, Pl. 65, Fig. 11), appeared at the base of Sequence 8 (Fig. 6). This rather rare species differentiates the thick upper part of the *Fryxellodontus inornatus* Subzone from the thin lower part of the subzone that is within Package 7C. One new trilobite, *Apoplanius rejectus*, also occurs at the base of Sequence 8 and likewise differentiates the major part of the *Missisquoia typicalis* Subzone that is within Sequence 8 from the minor part of the subzone that is within Package 7C (Fig. 4). Packages 7B, 7C, and the lower part of Sequence 8 comprise Stage 1 of biomere development, as delineated by Stitt (1971a, 1975). He characterized this stage as a time when new lineages appeared after a crisis interval at the top of the previous biomere. The crisis interval in this case was the *Eurekia apopsis* Zone, Packages 6C–7A. During deposition of Packages 7B and 7C, taxa of the shallow marine fauna were stressed, and ultimately new taxa, perhaps better adapted to the changing conditions, filled new niches. The final punctuation of sea-level fall at the top of the Package 7C resulted in the smallest response by the fauna. This seemingly was the time of greatest restriction of the shallow marine environment during actual subaerial exposure of part of the carbonate platform. This exposure is recorded as an unconformity at the top of the Lawson Cove Bed but also as a correlative conformity in the deeper parts of the House Range Embayment. The Lange Ranch Lowstand records a well documented example of the response of pioneer taxa to changing environments following an interval of major faunal turnover.

Conodonts become much more abundant at the base of Package 7C compared with older strata. The increase is subtle but is noted in many sections in North America. Table 4 shows that the statistic "conodonts per kilogram dissolved" increases abruptly at sample LCL-LD191, the white chert bed, and this abundance continues up to LCL-LD196. Abundance decreases in Sequence 8, but this reduction is within a thick stromatolite-thrombolite bioherm, a lithology that typically yields few conodonts. Conodonts are abundant in Sequence 8 in other non-microbial carbonate facies. Conodont abundances increase in Sequence 9 and generally remain at a level that is much higher than samples below the white chert bed at the base of Package 7C.

These faunas allow long-distance correlation of Package 7C and the exposure surface at its top (Miller, 1992). At Lange Ranch, Package 7C is preserved as small erosional remnants between two truncation surfaces (Fig. 39; see also Miller, 1992, Fig. 3), although the evidence for this conclusion is somewhat complex. The lower surface truncates ooids in a burrowed grainstone that contains trilobites of the *Eurekia apopsis* Zone (Taylor, 1984) and a conodont fauna that includes *Cordylodus andresi* but lacks *C. proavus*. This faunal association characterizes Package 7A. Above this lower truncation at the top of 7A are small thrombolites, which are truncated by a second, steeply inclined surface that cuts across the lower surface (Fig. 39). Strata above the thrombolite yield trilobites of the *Missisquoia typicalis* Subzone and conodonts of the *Fryxellodontus inornatus* Subzone. No fauna has been recovered from such erosional remnants because of their small size, so it is unclear whether they are from Package 7C or from the base of Sequence 8. However, about 900 m to the northwest at the Threadgill Creek section (Fig. 13), a thrombolite unit at the same stratigraphic position is ca. 15 inches (38 cm) thick and has truncation surfaces at its base and top. This thicker thrombolite bed has the lowest occurrence of *F. inornatus* and is considered to be coeval with the smaller remnant illustrated in Figure 39. Package 7C thus has thrombolitic mounds at Lange Ranch as well as at Threadgill Creek. Overlying strata at both sections are assigned to Sequence 8.

A similar lithologic and faunal succession occurs in the Dayangcha section in Jilin Province, North China (Chen and Gong, 1986; Chen et al., 1988). In this section the lowest ca. 1.5 m of the *Cordylodus proavus* Zone contains saukiid trilobites, which are characteristic of strata as young as Package 7A. Above this interval is a bed that has the lowest occurrence of *Fryxellodontus inornatus*, and the next bed is a stromatolite biostrome (Fig. 43). The top of the stromatolite bed is an irregular karst exposure surface. This succession is analogous to the stromatolite (Lawson Cove Bed) at the top of Package 7C in the Ibex area and is analogous to the thrombolite unit in Texas. We consider the microbial units in these three areas to be coeval based on their proximity to the lowest occurrence of *F. inornatus*

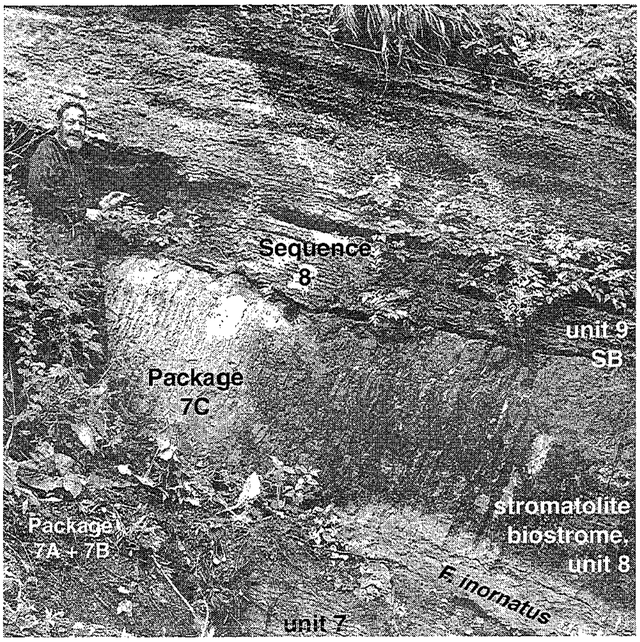


Figure 43. Probable karst Sequence Boundary (SB) separating Package 7C from Sequence 8 at Dayangcha section, Jilin Province, North China. Units 7, 8, 9 are as used by Chen et al. (1988, Fig. 6). Lowest occurrence of Fryxellodontus inornatus *in this section is just below stromatolite biostrome, unit 8, and is slightly below a sequence boundary. This biostrome thus correlates with Lawson Cove Bed in Utah (compare with Figures 38, 40–42) and the thrombolite remnant in Texas (compare with Figure 39). Don Winston holds a hammer for scale.*

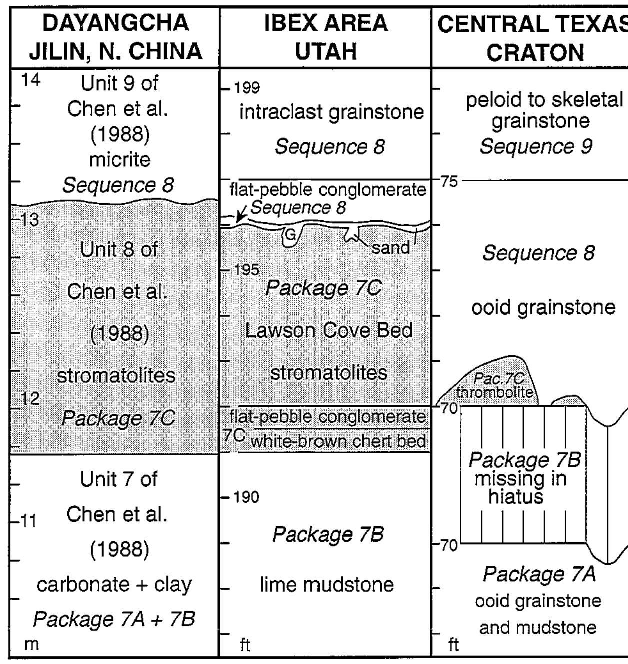


Figure 44. Correlation of microbial lithologies assigned to Package 7C in North China (Figure 43), Utah (composite of Figures 38, 40–43), and Texas (Figure 39). G = sand-filled grikes. Correlation is based on lowest occurrence of Fryxellodontus inornatus *at the base of each shaded interval.*

(Fig. 44). Exposure of strata below the stromatolite bed in China is not as good as in Utah and Texas, so it is unclear if there are additional erosional surfaces in the Dayangcha section. Miller (1992, Fig. 4) discussed another analogous section at Wushan, North China. In this section, strata representing Packages 7B or 7C are overlain unconformably by strata that correlate to Sequence 8. Recognition of these packages in such widely separated areas (Utah, Texas, China) suggests that these packages are related to true eustatic fluctuations and are not caused solely by local tectonics that also affected accommodation in western Utah.

SEQUENCE 8

Sequence 8 is in the upper part of the Lava Dam Member, although the highest beds of the Lava Dam are assigned to Sequence 9. Sequence 8 is not divided into packages. The thickness at Lawson Cove is 84 ft (25.6 m), and the thickness ranges from a maximum of 91 ft (27.7 m) at Sneakover Pass to a minimum of 36 ft (11.0 m) in the Drum Mountains. Sequence 8 and Package 7C combined are 113 ft (34.4 m) thick at Chalk Knolls South. Sequence 8 is assigned to the *Fryxellodontus inornatus* Subzone. Sequence 8 includes most of the *Missisquoia typicalis* Subzone, but the base of the subzone is in Sequence 7 and its top is in Sequence 9.

At Lawson Cove the basal beds of Sequence 8 are flat-pebble conglomerate and intraclast grainstone that overlie the Lawson Cove Bed (Fig. 40), and the next beds are lime mudstone that grade laterally and vertically into microbial boundstone. Most of Sequence 8 in the lower segment of the section consists of unbedded thrombolitic and stromatolitic boundstone that forms a local bioherm. Equivalent beds 100 m to the west, in the middle segment of the section, are thick to massive beds of lime mudstone and peloid to fine intraclast grainstone with virtually no chert. The bioherm in the lower segment is terminated abruptly at a planar truncation surface that forms the top of Sequence 8 (Fig. 45). Conodonts from just below this surface (sample LCL-LD277) are discolored due to weathering during subaerial exposure. It is difficult to find the equivalent horizon in the middle segment of the section, even though it is only about 100 m to the west, because the bioherm is not present there. However, we have identified a truncation surface at composite footage 331 ft (100.9 m) in the middle segment that appears to be the same horizon

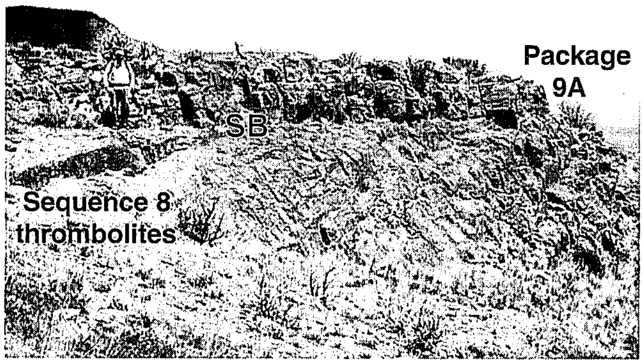


Figure 45. Eastward view of sequence boundary (SB) separating thrombolite mound of Sequence 8 from strata of Package 9A. J.F. Miller stands at sequence boundary, at 278 ft in lower segment of Lawson Cove section; this surface truncates the stromatolite mound and may be an unconformity. Compare with Figure 46.

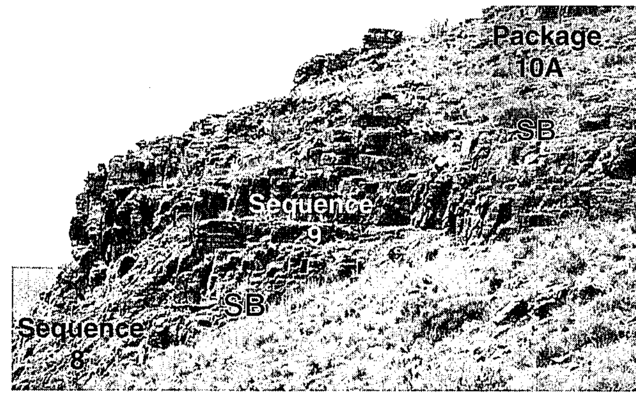


Figure 46. Westward view of Sequences 8–10 in middle segment of Lawson Cove section. Lower sequence boundary (SB) is at base of Sequence 9; upper SB is at base of Sequence 10, at top of Notch Peak Formation. Upper SB is at exposure of coarse Symphysurina *coquina, slightly right of that specific* Ephedra *bush, at 275 ft in measured section. Package 10A is very cherty limestone. Sequence 9 is 27 ft (8.2 m) thick and probably is unconformable at the base; Sequence 9 is 156 ft (78 m) thick at Chalk Knolls South and is unconformable at the top.*

as the top of the bioherm (Fig. 46). This surface is the top of Sequence 8 in the middle segment of the Lawson Cove section.

Quartz sand is moderately abundant at the base of Sequence 8, but most of the interval has very little sand (Tables 9, 10; Fig. 17). Sequence 8 is interpreted as a major deepening (interval of increasing accommodation); the stromatolite bioherm grew rapidly enough to fill available accommodation. The truncation surface at the top of this sequence seems to record a time of subaerial exposure (accommodation minimum).

Sequence 8 is only 5 ft (1.5 m) thick in the Lange Ranch section, Texas. The base of the sequence is an unconformity, but the upper boundary in Texas is conformable, so it is likely that much of the lower part of Sequence 8 is missing at Lange Ranch.

SEQUENCE 9

Sequence 9 includes the upper beds of the Lava Dam Member. The thickness in the lower segment of the Lawson Cove section is 18 ft (5.5 m) and 27 ft (8.2 m) in the middle segment. The difference in thickness between the two segments may relate to the amount of synoptic or erosional relief above the bioherm (lower segment) versus above the bioherm flank (middle segment). This sequence thickens northward by a factor of 9 from Lawson Cove on the Wah Wah Arch to Chalk Knolls South in the House Range Embayment, where Sequence 9 is 156 ft (47.5 m) thick. North of there the sequence thins to only 17.5 ft (5.3 m) in the Drum Mountains section, located on the Tooele Arch (Table 23).

Sequence 9 strata form a bold cliff in several sections (Figs. 33, 45, 46). Just below the top of Sequence 9 a prominent red argillaceous parting occurs in several sections at the base of a 3 in (8 cm) coarse coquina of the trilobite *Symphysurina.* This coquina is present in Ibex sections from Lawson Cove as far north as Section A. The top of the bed, which typically forms a more obvious bedding plane than the red parting, is used together with the appearance of abundant chert in overlying beds as the Notch Peak-House contact and as the top of Sequence 9.

Strata of Sequence 9 are assigned to the *Clavohamulus elongatus* Subzone of the *Cordylodus proavus* Zone, and the *Symphysurina* coquina (top bed of Sequence 9) is assigned to the *Hirsutodontus simplex* Subzone of the *C. intermedius* Zone. Sequence 9 is assigned to parts of two trilobite zones. The lower strata are assigned to the *Missisquoia typicalis* Subzone of the *Missisquoia* Zone. The upper part (9 ft (2.7 m) at Lawson Cove) of Sequence 9 is assigned to the *Symphysurina brevispicata* Subzone of the *Symphysurina* Zone, and the base of this trilobite zone is within the *Clavohamulus elongatus* Subzone (Figs. 6–8).

Package 9A

Package 9A includes most of Sequence 9. From Lawson Cove northward to Sevier Lake, lithologies include relatively thin successions of cherty lime mudstone to grainstone. In sections north of Skull Rock Pass, strata are much thicker (Fig. 31) and are almost entirely stromatolitic boundstone. The two lithologies are interbedded at Sevier Lake Corral. Thicknesses range from 16 ft (4.9 m) at Lawson Cove to 156 ft (78.0 m) at Chalk Knolls South. Package 9A thins to

17.5 ft (5.3 m) in the Drum Mountains (Table 23), where it is mostly stromatolitic dolomite. Strata from the lower part of Package 9A have very little quartz sand, but the amount generally increases upward (Fig. 17). It records a rapid relative rise of sea level (increase in accommodation) following probable subaerial exposure at the base of the package (Fig. 45) followed by an upward-shallowing succession.

There is a reciprocal thickness pattern between Sequences 8 and 9 in the Lange Ranch section, Texas compared to the Lawson Cove section, Utah. Sequence 8 is thick and Sequence 9 is thin at Lawson Cove, but the reverse is true at Lange Ranch.

All of Package 9A has conodonts diagnostic of the *Clavohamulus elongatus* Subzone, and the subzone continues into Package 9B. At Lawson Cove the lower 9 ft (2.7 m) has trilobites assigned to the *Missisquoia typicalis* Subzone, but the upper 7 ft (2.1 m) of the package is assigned to the *Symphysurina brevispicata* Subzone.

Package 9B—Terminal Package

Package 9B is the uppermost few feet of the Notch Peak Formation. It is a thin interval that ranges from 2 ft (0.6 m) thick in the lower segment of Lawson Cove to 4.5 ft (1.4 m) at Lava Dam Five. The package is less obvious at Lawson Cove than at other sections, but it is clearly manifested in sections that have stromatolites near the top of the Lava Dam Member. In those sections the base of this thin package truncates underlying stromatolites (Fig. 47). This surface is typically planar but may be strongly stylolitized in some sections. The package consists of grainstone and lime mudstone and has the *Symphysurina* coquina at the top.

The package is very thin, but it contains at the base a characteristic high quartz sand content that decreases upward. Three conodont samples were taken from this terminal package in the middle segment at Lawson Cove. The lowest sample is at the base of the package and has 64.3 per mil quartz sand, double the value of the underlying sample (Table 13, Fig. 17). The middle sample has 16.3 per mil sand, and the top sample (*Symphysurina* coquina) has 5.4 per mil sand. The next sample, at the base of the House Limestone and base of Sequence 10, has an increase in quartz sand to 23.1 per mil. At the lower segment, three samples collected from this package (Table 11) show a similar trend. This pattern indicates a brief drop in sea level at the base of the package, followed by a relative rise. The base of Sequence 10 is the start of the Basal House Lowstand.

A major change in the conodont fauna takes place slightly below, within, and slightly above this package. *Monocostodus sevierensis* and *Utahconus utahensis* appear within this package at Lava Dam Five and occur with typical taxa of the *Clavohamulus elongatus* Subzone (Hintze et al., 1988, Table 3, sample LD-250). *Hirsutodontus simplex* occurs in

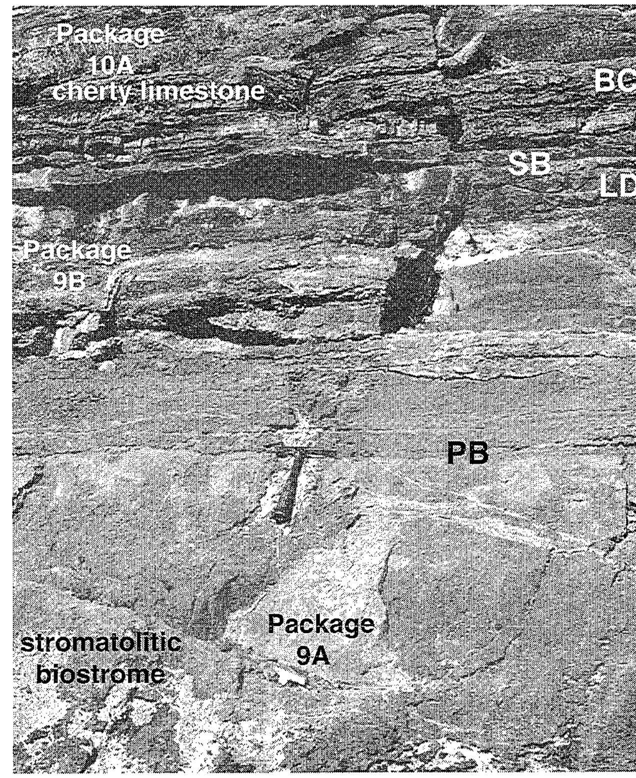


Figure 47. Packages 9A, 9B, and 10A at Sevier Lake Corral section, between north and south segments. Upper part of Lava Dam Member, Package 9A, contains a stromatolitic biostrome in this area, which is truncated at hammer head. PB = package boundary at base of thin Package 9B, top strata of Lava Dam Member (LD) of Notch Peak Formation. SB = sequence boundary at base of Package 10A, cherty limestones of basal Barn Canyon Member (BC) of House Limestone.

the top bed of this package (*Symphysurina* coquina and base of *H. simplex* Subzone). *Cordylodus intermedius* appears slightly higher, in the lower beds of Sequence 10. Similar faunal changes occur in the lower and middle segments of the Lawson Cove section (Tables 2, 3), where the transition is documented better because of very close sample spacing. In the middle segment, *Monocostodus sevierensis* occurs as low as sample LCM-LD-270, 2 ft (0.6 m) below this package. Samples LCM-LD272 and 274 contain three species of *Clavohamulus* together with the lowest occurrence of *Utahconus utahensis*. Sample LCM-LD275 (*Symphysurina* coquina) has the highest occurrence of *Clavohamulus* and the lowest occurrence of *Hirsutodontus simplex*. *Cordylodus intermedius* begins 4 ft (1.2 m) higher, in sample LCM-HL279, within Sequence 10. These occurrences show that the major faunal change that takes place across the Notch Peak-House contact is transitional and generally occurs within Package 9B.

The pattern of step-wise faunal turnover also demonstrates conformity across this sequence boundary at Lawson Cove. This conformity occurs at least as far north as Section A. At Chalk Knolls South the Notch Peak-House contact is an irregular karst surface at the top of Sequence 9, which is thick and consists almost entirely of stromatolites and thrombolites. These microbial rocks are assigned to Package 9A (Fig. 48), and Package 9B is missing. The lower package of Sequence 10 is also missing in this unconformity, which can be traced northward to the Drum Mountains.

SEQUENCE 10

Sequence 10 includes most of the lower half of the Barn Canyon Member of the House Limestone. The thickness of Sequence 10 shows an inverse relationship to Sequence 9; it is thin in the north but thickens southward by a factor of 10 (Fig. 31). Sequence 10 is 132 ft (40.2 m) thick at Lawson Cove and 13.5 ft (4.1 m) at the Drum Mountains section. It is divided into three packages.

At Lawson Cove the boundaries of Sequence 10 coincide almost exactly with the boundaries of the *Cordylodus intermedius* Zone. The base of the zone is at the base of the *Symphysurina* coquina, whereas the base of the sequence is a few inches higher, at its top. This coquina yields the lowest *Hirsutodontus simplex* at Lawson Cove and at Lava Dam Five, and this coincidence is consistent among most Ibex sections. The top of Sequence 10 at Lawson Cove is a major topographic break (cliff top) that coincides with the top of the *C. intermedius* Zone, and overlying slope-forming strata have fauna diagnostic of the *C. lindstromi* s. l. Zone (Fig. 49). A significant turnover of conodont taxa occurs at this sequence boundary at Lawson Cove and Lava Dam North (Figs. 8, 10). All of Sequence 10 is within the *Symphysurina brevispicata* Subzone, although some older and younger strata are also assigned to this trilobite subzone. The brachiopod *Eurytreta sublata* occurs through all of Sequence 10, and a different species of the genus begins at the base of Sequence 11.

Package 10A—Basal House Lowstand

Package 10A is the Basal House Lowstand (Fig. 3), and the base of the package is at the base of the House Limestone. The package has large amounts of white to brown chert interbedded with sandy carbonates, and the top of the package is where the chert ends. These strata are 42 ft (12.8 m) thick at Lawson Cove and thin northward to 13 ft (4.0 m) at Sneakover Pass (Table 23). The package pinches out northward and is absent at Chalk Knolls South and in the Drum Mountains.

Package 10A carbonate lithologies at Lawson Cove include minor lime mudstone and more common laminated fine grainstone, skeletal and intraclast grainstone, and minor

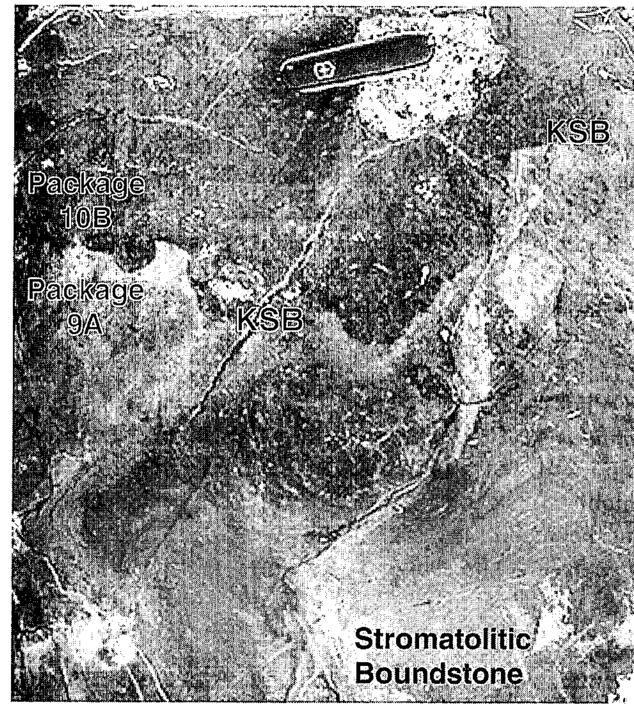


Figure 48. Karst sequence boundary (KSB) separates Package 9A (top of Notch Peak Formation) from Package 10B (base of House Limestone) at 580 ft level in Chalk Knolls South section. Packages 9B (including Symphysurina *coquina) and 10A (very cherty limestone) are missing at this boundary, which formed by subaerial dissolution. Swiss Army knife is 3.5 in (9 cm) long.*

flat-pebble conglomerate. Package 10A also includes 20 to 60 percent nodular and bedded chert that is white to brown and rarely black (Fig. 50). This abundant chert commonly is laminated and is similar to the white to brown chert bed at the base of Package 7C (Fig. 38). We interpret the package as a lowstand deposit because significant amounts of quartz sand occur in the interbedded limestones (Fig. 17). Much more of the original amount of siliciclastic material seemingly has been recrystallized to chert. We interpret the Basal House Lowstand as recording a rapid drop in sea level at the base of Package 10A followed by a slow rise of sea level and static accommodation during which lowstand conditions persisted. Another brief drop in sea level occurred at the top of the package (Fig. 17). During deposition of Package 10A, the available accommodation was quickly filled by locally produced carbonate sediment and by abundant quartz sand derived from exposed source areas.

The quartz sand concentration at the top of Package 10A shows an interesting pattern (Table 14). Samples in the upper part of the package generally have higher sand content than the lower part of the package, probably because

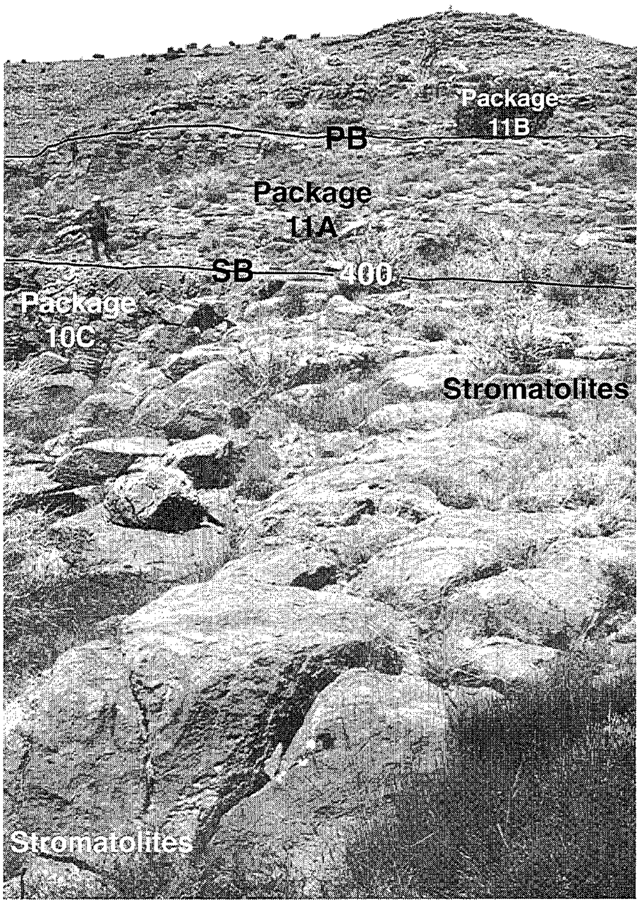


Figure 49. Stromatolites at top of Package 10B exposed below lower part of Sequence 11. R. S. Nicoll stands at sequence boundary (SB), at 400 ft in middle segment of Lawson Cove section. PB = Package Boundary between Packages 11A and 11B. Both boundaries emphasized by black lines. Top of hill is top of middle segment of section, but not all of the upper part of the section is visible from this point of view.

more of the sand is recrystallized to white chert in the lower part. Samples LCM-HL305 upper and 308 have very low sand content, 2.1 and 6.5 per mil, and these samples are above most of the white chert. The next sample, LCM-HL310, is at the top of Package 10B and is also at the top of a second, thin interval of white chert from 306–310 ft in the described section. At that level the sand increases to 53.1 per mil. Overlying samples within Package 10B have very low sand content. The sudden influx of sand represented by sample HL310 and the thin white chert reflect a brief, sharp drop in relative sea level within the upper part of the *Hirsutodontus simplex* Subzone. The same brief drop in sea level is preserved as a karst horizon near the top of the *H. simplex* Subzone in the Main Elk Creek section, located on the western flank of the Transcontinental Arch

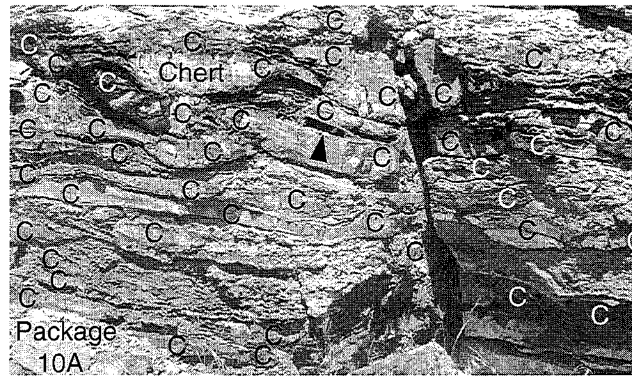


Figure 50. Abundant white to brown chert (C) at 283 ft in middle segment of Lawson Cove section. Such cherty limestone characterizes Package 10A and is diagenetically recrystallized peritidal deposits of carbonate mixed with quartz sand. Black triangle near center of photo points to Swiss Army knife, 3.5 inches (9 cm) long. See Figure 46 for general view of strata.

in Colorado (Myrow et al., 1999, Fig. 16). Two similar karst horizons at Main Elk Creek coincide with lowstands at the base of Sequence 10 and the base of Sequence 8. Package 10A is only 2.5 ft (0.8 m) thick in the Lange Ranch section, Texas (Fig. 14), where it is recognized by its relatively high quartz sand content and by the occurrence of very coarse flat-pebble conglomerate.

All of the Basal House Lowstand is assigned to the *Hirsutodontus simplex* Subzone, which continues into younger strata. These strata are also assigned to the *Symphysurina brevispicata* Subzone, but the subzone includes both older and younger strata.

Package 10B—Deepening

Package 10B is 65 ft (19.8 m) thick at Lawson Cove, and the base of the package is at the highest occurrence of white to brown chert. The top is at a widespread stromatolite biostrome; the top is also indicated by an increase in quartz sand. Thickness is greatest in the Wah Wah Arch sections, with a maximum at Lawson Cove of 65 ft (19.8 m). Thickness is less in the House Range Embayment, with a minimum of 26.5 ft (8.1 m) at Notch Peak. Package 10B is 14.5 ft (4.4 m) thick at Lange Ranch, Texas.

Lithologies at Lawson Cove include lime mudstone (some is argillaceous), fine grainstone (some is laminated), and minor peloid to ooid and skeletal grainstone. Chert nodules and stringers are dark brown and less abundant than in Package 10A. Very small amounts of quartz sand occur in this package (Fig. 17). We interpret Package 10B as reflecting an initial relative rise of sea level and increase in accommodation that eventually covered siliciclastic source areas, followed by a period of general stability of sea level (uniform accommodation).

At Lawson Cove the lower 17 ft (5.2 m) of Package 10B is assigned to the *Hirsutodontus simplex* Subzone; the remaining strata are assigned to the *Clavohamulus hintzei* Subzone, which includes the next package. The entire interval is within the *Symphysurina brevispicata* Subzone.

Stratigraphic relationships at the Drum Mountains and Chalk Knolls South sections reinforce the interpretation that the base of the House Limestone is a major sequence boundary that records hiatus. The Drum Mountains are located on the south flank of the Tooele Arch, and it is clear that the arch was exposed to erosion during deposition of the lower part of Sequence 10. Package 10A is absent, and the base of Package 10B in the Drum Mountains section is a conglomerate containing chert and carbonate pebbles and cobbles in a carbonate matrix (Fig. 51). Conodonts from the matrix and carbonate clasts contain a mixed-age fauna that includes *Clavohamulus elongatus* and *Hirsutodontus simplex*. These species typically do not occur together except in the *Symphysurina* coquina, the top bed of Package 9B. The beds below the conglomerate are upper Notch Peak Formation and are assigned to Package 9A; Package 9B (including the *Symphysurina* coquina) is absent. Sequence 9 in this section contains abundant *C. elongatus*, and apparently some specimens in clasts derived from the top of that sequence were reworked into the conglomerate at the base of Sequence 10.

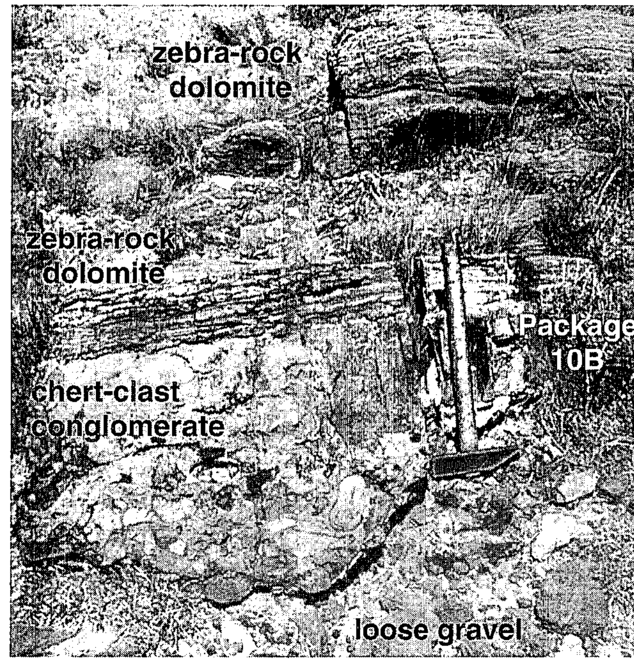


Figure 51. Chert-clast conglomerate and zebra-rock dolomite at base of House Limestone; base of conglomerate is at 386.5 ft in Drum Mountains section. Strata are assigned to Package 10B; Packages 9B and 10A are missing in this section. Hammer head is 6.6 inches (17 cm) across.

The presence of white chert clasts in the basal conglomerate of Package 10B suggests that some of Package 10A may have been deposited in this general area, although it is not present now. Such chert is typical of Package 10A farther south. This kind of cherty carbonate must have been deposited in the area and then removed by erosion. The chert was then rounded during transport, deposited during the subsequent transgression, and preserved as the basal chert conglomerate of Package 10B in the Drum Mountains. Formation of this conglomerate may be related to the regressive event separating Packages 10A and 10B.

The absence of Package 9B and 10A extends as far south as Chalk Knolls South. The Notch Peak-House contact in that section is a karst truncation surface with several inches of local relief (Fig. 48). Overlying strata of Sequence 10 are significantly thinner compared to sections farther south (Fig. 31). The Notch Peak-House contact interval (Packages 9B and 10A) thus marks a fundamental change in siliciclastic content (Fig. 17) and regional thickness patterns (Fig. 31) on the western Utah carbonate platform. These changes imply that this interval records a major lowering of sea level followed by a rise in sea level during Package 10B.

Package 10C—Filling Accommodation

Package 10C is the interval between a widespread stromatolite biostrome and a major regression at the top of Sequence 10. The base is at the lowest stromatolite bed or a coincident abrupt increase in quartz sand (Fig. 17) in the upper part of the *Clavohamulus hintzei* Subzone, to which all of Package 10C is assigned. The top of the package is at an increase in quartz sand at the base of the *Cordylodus lindstromi* s. l. Zone. Package 10C ranges in thickness from 27 ft (8.2 m) at Sevier Lake Corral to 2.5 ft (0.8 m) at Chalk Knolls South; it is 12.5 ft (3.8 m) thick at Lange Ranch, Texas.

A thin unit of stromatolites or thrombolites occurs at the base of Package 10C at Lawson Cove, Lava Dam North, Sevier Lake, Tank Canyon, and Section A. This horizon typically also has an abrupt increase in quartz sand, and this feature is used to place the base of the package at Sevier Lake Corral and at Lange Ranch (Fig. 17). The top of the thrombolite unit at Section A is red and has abundant pseudomorphs of iron oxide after pyrite, suggesting it was subaerially exposed. If one interprets these features as indicating exposure, it would imply an abrupt but brief relative drop in sea level, followed by a sea level rise. Stromatolite beds are common in Package 10C at Lawson Cove (Fig. 49), indicating that carbonate sedimentation was keeping pace with accommodation. A thin stromatolite bed at Chalk Knolls South is virtually the entire interval of Package 10C, and the top of the bed is a truncation surface at the base of Sequence 11.

Packages 10B and 10C cannot be separated in the Drum Mountains, but the composite interval is only 13.5 ft (4.1 m) and reflects thinning on the Tooele Arch. The upper part of Sequence 10 is also thin at Chalk Knolls South, noted above. Figure 51 shows that zebra-rock dolomite comprises most of these strata in the Drum Mountains. As in the case of zebra-rock dolomite in the Hellnmaria Member, we interpret this lithology as indicating lowstand or stillstand conditions; in the Drum Mountains these conditions followed deposition of the chert-clast conglomerate of Package 10B. The zebra rock records a time of little production of accommodation, when peritidal to supratidal conditions prevailed. Conodonts are rather abundant in this unusual lithology, which may reflect its condensed depositional history, so the lower 8.5 ft (2.6 m) of Package 10C can be assigned to the *H. simplex* Subzone and the upper 5 ft (1.5 m) to the *Clavohamulus hintzei* Subzone.

SEQUENCE 11

Strata of Sequence 11 are assigned to the middle and upper parts of the Barn Canyon Member and to the lower part of the overlying Burnout Canyon Member. The Drum Mountains Lowstand is at the base, the Stonehenge Transgression comprises most of the sequence, and at the top is the lower part of the Burnout Canyon Lowstand. Sequence 11 is 168 ft (51.2 m) thick at Lawson Cove. The maximum thickness is 195.5 ft (59.6 m) at Section A, and the minimum thickness is 107 ft (32.6 m) in the Drum Mountains (Fig. 31). The siliciclastic content of Sequence 11 is quite variable, but it generally increases upward (Fig. 17).

At Lawson Cove, conodonts in Sequence 11 are assigned to the *Cordylodus lindstromi* s. l. Zone, the *Iapetognathus* Zone, the *Cordylodus angulatus* Zone, and the lower part of the thick *Rossodus manitouensis* Zone. Conodont faunas are better documented at Lawson Cove than at Lava Dam North, but both sections show the same relationships. At Lawson Cove, trilobites from Sequence 11 are assigned to the upper part of the *Symphysurina brevispicata* Subzone, the *S. bulbosa* Subzone, and to the lower part of the *S. woosteri* Subzone of the *Symphysurina* Zone. The common acrotretoid brachiopod *Eurytreta* cf. *bisecta* (Matthew) appears at the base of Sequence 11, and its range extends at least as high as the top of the House Limestone at Lava Dam North.

Sequence 11 consists of seven distinct packages that range in thickness from 9 to 61 ft (2.7 to 18.6 m) at Lawson Cove. Several of the regressive intervals at the package boundaries have been recognized by previous authors and named as specific eustatic events. The lower packages of Sequence 11 can be correlated very precisely using key beds, carbon-isotope signatures, and successions of conodont and trilobite faunas (Fig. 52).

Package 11A—Lower part of Drum Mountains Lowstand

Package 11A is the lowest package of Sequence 11 and is named herein the Drum Mountains Lowstand because the interval is very condensed there. Package 11A is 16.5 ft (5.0 m) thick at Lawson Cove and Section A; the maximum thickness is 17 ft (5.2 m) at Sevier Lake Corral. The base of Sequence 11 is at 400 ft (121.9 m) in the Drum Mountains section, and the top of Package 11B is only 8 ft (2.4 m) higher. It is impossible to determine from available faunal evidence if Packages 11A and 11B are both present in this thin interval. The base of Package 11A is a truncation surface at Chalk Knolls South. Package 11A is missing entirely in the Lange Ranch section in Texas.

At Lawson Cove there is an abrupt lithofacies shift at the base of Package 11A. Stromatolites at the top of Sequence 10 form a cliff; the lower 1 ft (0.3 m) of Package 11A is covered, and the remainder is a slope with relatively poor exposure (Fig. 49). There are abundant oncoids at the base of Package 11A, and lithologies include lime mudstone, laminated fine grainstone, peloid to intraclast grainstone, and minor intraclast conglomerate.

The quartz sand content at the base of this lowstand package at Lawson Cove increases by a factor of five compared with the top of Sequence 10 (Fig. 17). The sand diminishes gradually and is reduced near the top compared with the base, but there is a second increase in sand content at the top of the package. These changes in sand content are important in identifying the base and top of this package, but the actual top is placed at a truncation surface. The base of the package is interpreted as a rapid shallowing event followed by gradual deepening through most of the package. At the top is a second shallowing event that led to eventual subaerial exposure (accommodation minimum) at the top of Package 11A.

Package 11A is within the upper part of the *Symphysurina brevispicata* Subzone. The base of Package 11A at Lawson Cove is at the lowest occurrence of *Cordylodus prolindstromi,* and the top of Package 11A is only 2.5 ft (0.8 m) above the lowest occurrence of *C. lindstromi* s. s. Thus Package 11A includes the entire lower subzone of the *Cordylodus lindstromi* s. l. Zone, which correlates with the *Cordylodus prolindstromi* Zone of Shergold and Nicoll (1992) at Black Mountain, Australia. J. F. Miller attended a field trip to the Black Mountain section during the 1991 Ordovician Symposium held in Australia (Shergold et al., 1991). R. S. Nicoll demonstrated in the field several eustatic

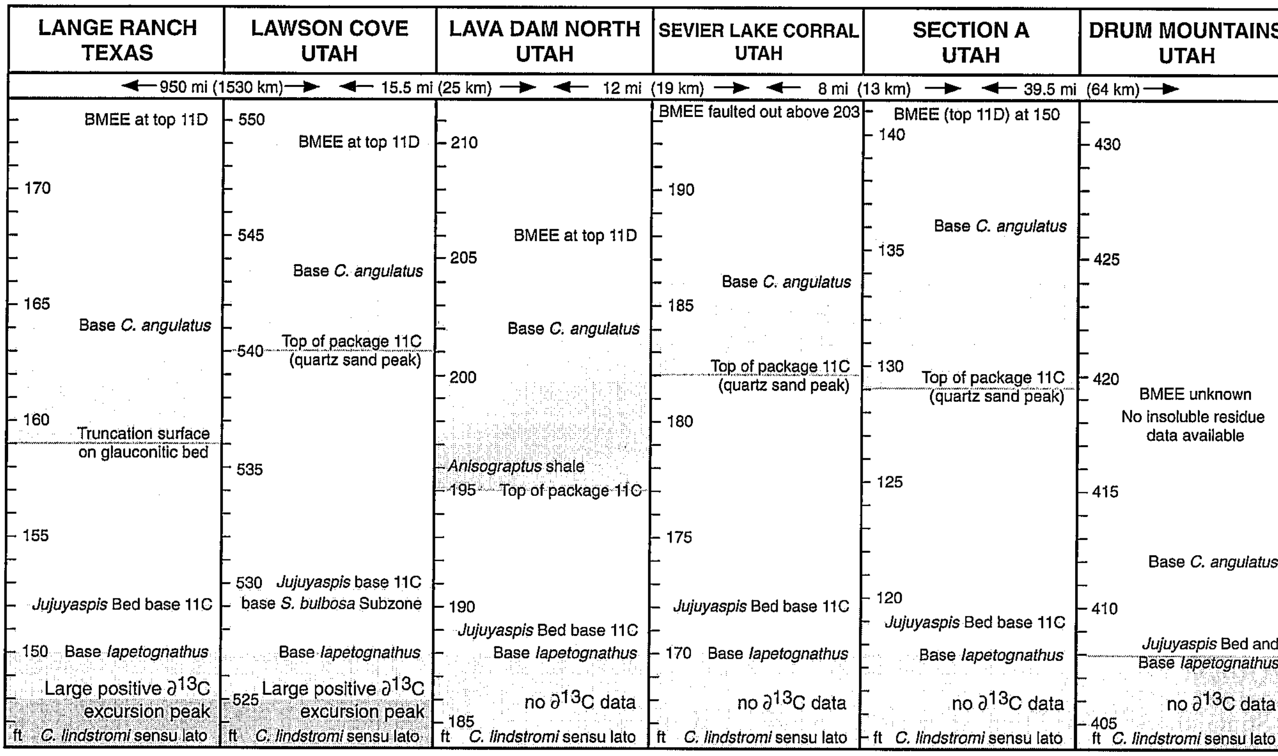


Figure 52. High-resolution correlation of Packages 11B–11E among sections in Utah and Lange Ranch section, central Texas. Strata are aligned at base of Iapetognathus *Zone, in upper part of Package 11B. Base of interval shown is within* Cordylodus lindstromi *s. l. Zone. Package 11C begins at base of* Jujuyaspis *bed and ends at quartz sand peak. One ft (0.3 m) above top of 11C at Lava Dam North is a thin,* Anisograptus*-bearing brown shale. Top of Package 11C at Lange Ranch is placed at truncation surface on glauconitic bed illustrated on Figure 55; younger strata are assigned to Package 11D and 11E. Black Mountain Eustatic Event (BMEE) is base of Package 11E, placed at a quartz sand peak. Vertical scale identical in all sections.*

events that were described by Nicoll et al. (1992), including a regression near the base of the *Cordylodus prolindstromi* Zone and evidence for a second regression near the base of the *C. lindstromi* Zone. These same two regressions are identified in the Ibex area at the bases of Packages 11A and 11B.

Erdtmann (1986) named the *Acerocare* Regressive Event for a regression recorded in strata just below the traditional Tremadocian Series in Norway. Probably Erdtmann's regressive event is equivalent to Package 11A and perhaps to part of Package 11B.

Package 11B—Uppermost Drum Mountains Lowstand and Subsequent Deepening

Package 11B begins with a relative sea-level rise above a basal truncation and ends with a relative sea-level drop. Package 11B ranges in thickness from 43 ft (13.1 m) at Sevier Lake Corral to 39.5 ft (12.0 m) at Section A and 21.5 ft (6.6 m) at Lawson Cove; its thickness cannot be determined in other sections. We include the lowest part of Package 11B within the Drum Mountains Lowstand along with Package 11A (Fig. 2), and part or all of both packages may be a hiatus in some platform and cratonic settings.

The base of the package at Lawson Cove is a truncation surface on a lime mudstone bed. The surface has abundant iron oxide pseudomorphs after pyrite and is overlain by intraclast grainstone and flat-pebble conglomerate. This truncation surface has also been identified in described unit 17 at Section A (Fig. 53), where it consists of a planar truncation overlain by thin pedestals of silty carbonate. This silty carbonate appears to have been eroded while it was still soft sediment. The underlying planar truncation is on a lime mudstone bed that was not affected when the overlying sediment was eroded, indicating that the bed probably was lithified. We interpret this as a subaerial exposure surface because it also can be correlated to other intervals where strata are missing, such as in Texas.

At Lawson Cove the top of Package 11B is a marker bed with abundant black lingulid brachiopods (probably

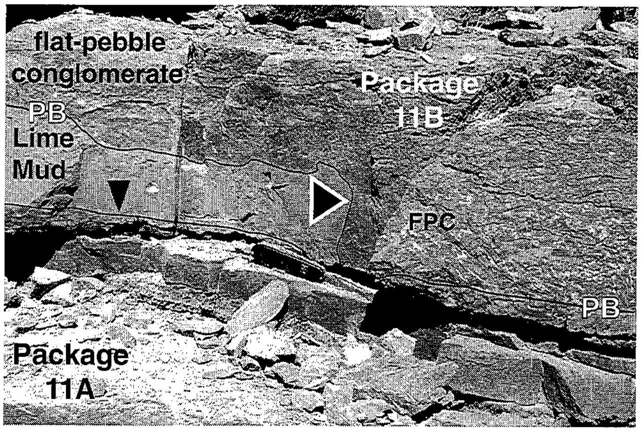


Figure 53. Complex package boundary (PB) between Packages 11A and 11B at 78 ft in described unit 17 of Section A, central House Range. Small, black triangle points to planar truncation surface. Upper and right points of white-rimmed triangle point to irregular truncation surface that cuts across lime mudstone bed and cuts down to lower truncation surface. Flat-pebble conglomerate (FPC) fills irregularities along upper truncation surface. Both truncation surfaces emphasized by black lines. Bottom point of white-rimmed triangle points to Swiss Army knife, 3.5 inches (9 cm) across.

Lingulella? incurvata Popov, Holmer, and Miller) that are about 5 mm long. This marker bed can be traced along strike to near the upper segment of the Lawson Cove section, but such a bed is not present in other sections. The overlying brown trilobite grainstone bed has a large increase in quartz sand, which marks the base of the next package (*Jujuyaspis* bed).

Strata in Package 11B include intraclast to skeletal grainstone, laminated fine grainstone, and lime mudstone. At Lava Dam North lithologies are similar and also indicate high energy, but Package 11B can not be clearly differentiated from Package 11A because of limited exposure and conodont collections. At Lawson Cove the base of Package 11B has rather high quartz sand content, but the amount is lower in most of the package (Table 14, Fig. 17). Package 11B appears to record abrupt shallowing with development of a truncation surface, followed by a relative rise in sea level and increase in accommodation through most of the package.

Package 11B has a distinctive fauna. The package is assigned to the upper part of the *Symphysurina brevispicata* Subzone. Package 11B nearly coincides with the upper subzone of the *Cordylodus lindstromi* s. l. Zone, although the base of this subzone begins slightly below the base of the package. The top of Package 11B includes the lower 3 ft (0.9 m) of the *Iapetognathus* Zone. Package 11B is coeval with the lower part of the *Cordylodus lindstromi* Zone at Black Mountain, Australia, although that zone includes strata equivalent to the *Iapetognathus* Zone, which has not been identified in the Black Mountain section. The lowest occurrence of the siphonotretoid brachiopod *Schizambon typicalis* (Walcott) is 4 ft (1.2 m) above the base of Package 11B (Table 3), and it is a characteristic species as high as the upper part of Sequence 11. Ethington et al. (1987, Fig. 8.3) reported *Schizambon* sp. from the top of the House Limestone and the base of the Fillmore Formation.

A distinctive carbon-isotope signal occurs in the upper part of Package 11B. The peak of the largest positive carbon-isotope excursion in the Lawson Cove section (Ripperdan and Miller, 1995, Fig. 3) occurs at sample LCM-HL433, located 2 ft (0.6 m) below the top of the *Cordylodus lindstromi* s. l. Zone and 5 ft (1.5 m) below the top of Package 11B (Fig. 52).

Package 11B is 9.5 ft (2.9 m) thick at the Lange Ranch section, Texas. The top of Sequence 10 is an unconformity in that section, and the base of Sequence 11 is a conglomerate consisting of small round limestone pebbles. The pebble bed produces a mixed-age fauna including *Clavohamulus hintzei* and *Rossodus tenuis* (both diagnostic of Sequence 10), together with *Cordylodus lindstromi* s. s. (diagnostic of the upper part of the combined Packages 11A–11B). This mixing indicates that most of or the entire lower subzone of the *Cordylodus lindstromi* s. l. Zone has been eroded and is missing. This faunal mixing occurs in the lower 1–2 ft (30–60 cm) of Sequence 11; Miller and Stitt (1995) discussed this relationship. Because of a drafting error, the range chart in that report mistakenly showed the ranges of *Clavohamulus hintzei* and *Rossodus tenuis* extending into the base of the *Iapetognathus* Zone, which is one zone higher than they actually occur. Those species normally do not occur above the top of the *C. hintzei* Subzone. The presence of *C. hintzei* and *R. tenuis* in the basal beds of the upper subzone of the *Cordylodus lindstromi* s. l. Zone probably is because they are redeposited in the conglomerate pebbles, and the younger species *C. lindstromi* s. s. was deposited *in situ* in the conglomerate matrix. The simplest interpretation of the relationships near this unconformity is that Package 11A is missing, and Sequence 11 begins with Package 11B. The basal strata of Sequence 11 at Drum Mountains and at Lange Ranch both contain fauna diagnostic of Package 11B, so we conclude that the transgressive portion of Sequence 11 began with Package 11B.

Package 11C—Stonehenge Transgression and Siliciclastic Influx

Package 11C is 7 ft (2.1 m) thick at Lava Dam North and 14 ft (4.3 m) at Sevier Lake Corral. The base of Package 11C is at the base of a 1 ft (0.9 m) marker bed, a distinctive brown bioclast-intraclast grainstone that has high quartz sand content; the top of the package is at a brief but large influx of quartz sand. The basal grainstone contains abundant trilobites, including the olenid *Jujuyaspis borealis* (Fig. 8; Plate 1, Figs 23–27). This genus occurs near the base of the Tremadocian Series on several continents (Aceñolaza and Aceñolaza, 1992). This brown grainstone bed is a thin interval of lowstand strata and contains clusters of iron oxide crystals that are pseudomorphs after pyrite. This bed occurs at Lawson Cove, Lava Dam North, Sevier Lake, Sevier Lake Corral, Section A (Fig. 54), Chalk Knolls South, and Drum Mountains (Miller and Taylor, 1995). *Jujuyaspis borealis* was first identified in the Ibex area at the Drum Mountains section (Stitt and Miller, 1987), and the species has been identified from most of the other localities where this brown grainstone bed occurs. Package 11C is more or less normally developed in the Drum Mountains, in contrast to underlying strata, which are extremely thin.

At Lava Dam North Package 11C extends from 196 to 213 ft in the measured section, which crosses a small fault within the package (see description of units 26–27). Lithologies are similar to those at Lawson Cove but include a 4 inch (10 cm) brown shale at 207 ft (63.1 m) in the described section. This is the only shale we have seen in the House Limestone in the entire Ibex area, and it contains the lower Tremadocian planktic graptolite *Anisograptus matanensis* (see Miller et al., 1999).

Package 11C is characterized by high amounts of quartz sand compared with older strata (Fig. 17). The base of the package is at the start of this influx of sand, which we interpret to indicate the start of a minor drop in sea level and reduced accommodation. Most of the package records shallow, high-energy conditions and an interval deposited during a time of lowering sea level (low accommodation) recorded by increasing siliciclastic content. At Lawson Cove the shallowest part is at the top of the package, where siliciclastic content reaches 71.8 per mil. The same trend is recorded in a general way at Section A and Sevier Lake Corral.

Coeval strata at the Lange Ranch section in Texas have two important parallels with this interval in Utah (Fig. 52). The first parallel is the presence of the trilobite *Jujuyaspis borealis* at the base of the package, slightly above the base of the *Iapetognathus* Zone. The interval between the base of this zone and the trilobite bed is 3 ft (0.9 m) at Lawson Cove, 2 ft (0.6 m) at Lange Ranch, and 1.5 ft (0.5 m) at Lava Dam North. The second parallel is the presence of abundant quartz sand in the *Jujuyaspis* bed at Lawson Cove and Lange Ranch (Miller and Stitt, 1995, Fig. 1). At Lange Ranch quartz sand in this bed increases by a factor of 80 to 120 compared with beds below and above.

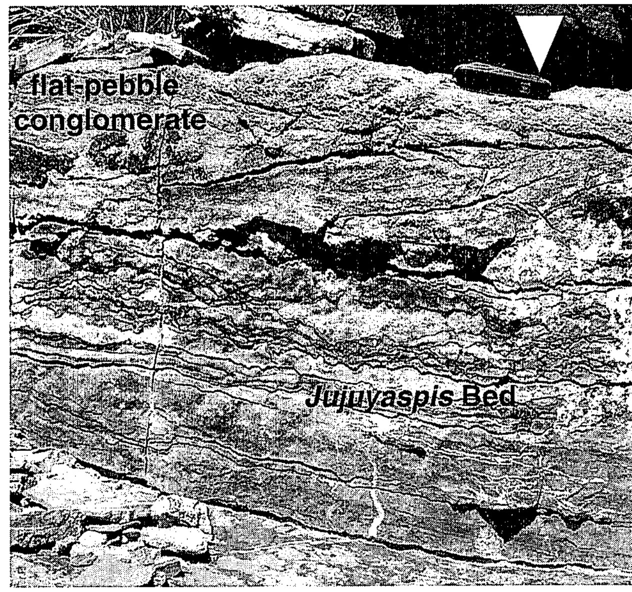


Figure 54. Distinctive brown grainstone bed containing Jujuyaspis borealis *and other trilobites at Section A, 119–120 ft in described section (CD-ROM). This bed is present in sections from Lawson Cove to the Drum Mountains and is the base of Package 11C. Arrow points to Swiss Army knife, 3.5 inches (9 cm) across.*

At Lawson Cove, Package 11C is characterized by important faunal changes among both conodonts and trilobites. The package is assigned to the *Iapetognathus* Zone. The base of the package is slightly above the base of the zone, and the top of Package 11C is 1.5 ft (0.5 m) below the base of the *Cordylodus angulatus* Zone. The marker bed with the abundant lingulid brachiopods at the top of Package 11B is the base of the *Symphysurina bulbosa* Subzone, and all of Package 11C is assigned to that subzone. The base of the package was chosen so as to correspond with an increase in quartz sand, but it is also the bed that contains the Tremadocian olenid trilobite *Jujuyaspis borealis*, so the base of Package 11C is essentially the base of the Tremadocian Series.

The upper part of Package 11C is at a peak of siliciclastic influx, indicating the peak of a brief regressive period within a generally transgressive interval. At Lawson Cove this peak is between the *Jujuyaspis* bed and the base of the *Cordylodus angulatus* Zone (Fig. 52). This regressive peak can be identified in other sections. Table 16 shows that the peak of siliciclastic influx in the Lava Dam North section is in the limestone bed just below the brown shale that contains graptolites; the shale itself is part of the peak of siliciclastic influx. Considering the limitations on precision imposed by sample spacing and exposure, this shale must be essentially equivalent to the top of Package 11C at Lawson Cove. At Lange Ranch, Texas there is a unique

3 inch (8 cm) grainstone bed that contains so much glauconite that it is green; this bed is at composite footage 158.9. The top of this bed is a sharp truncation surface that is overlain by tan grainstone (Fig. 55). The green bed records a brief regression that culminated in subaerial exposure. We correlate the regressive peak at the top of Package 11C at Lawson Cove with the brown shale at Lava Dam North and with this truncation surface at Lange Ranch (Fig. 52).

Package 11C records both a relative rise of sea level that is correlated with the base of the Tremadocian Series in Europe and also records a significant siliciclastic influx. Taylor et al. (1992) recognized a major transgression of this age in Pennsylvania, Maryland, and Virginia that they named the Stonehenge Transgression and correlated with transgression at the base of the Tremadocian Series. We follow Taylor et al. (1992) and adopt the term Stonehenge Transgression for this interval.

In Utah and Texas this relative rise of sea level can be tied to the Tremadocian Series because of the occurrence of *Jujuyaspis*, but this trilobite occurs in the second package of this stepped transgression. Overlying packages record progressive deepening. The implication of this multi-package transgression is that in different areas the oldest strata of Sequence 11 will undoubtedly represent different packages and thus will be different in age. Where the stratigraphic succession is fairly complete, such as Utah and Texas, the base of the transgression is older than the base of the Tremadocian Series.

Package 11D—Continued Deepening

Package 11D is a thin interval between two spikes of siliciclastic influx (Fig. 17) and records resumption of the relative sea-level rise associated with the Stonehenge Transgression. The minimum thickness is 9 ft (2.7 m) at Lawson Cove and the maximum is 21 ft (6.4 m) at Section A. The base of the package is at the peak of the previous regressive package and the package has a decrease in quartz sand, indicating a relative rise in sea level. The top of the package is at the next peak in quartz sand content. Lithologies include grainstone, flat-pebble conglomerate, and lime mudstone. At Lava Dam North the base of Package 11D is at the base of the brown shale, but the top of the package is 10 ft (3.0 m) higher. Lithologies in this interval are similar to those at Lawson Cove. The top of the package is faulted out at Sevier Lake Corral, and its thickness can not be determined at Chalk Knolls South or at the Drum Mountains section because of the lack of insoluble residue data.

The base of Package 11D is near or at the top of the *Iapetognathus* Zone and most of the package is within the

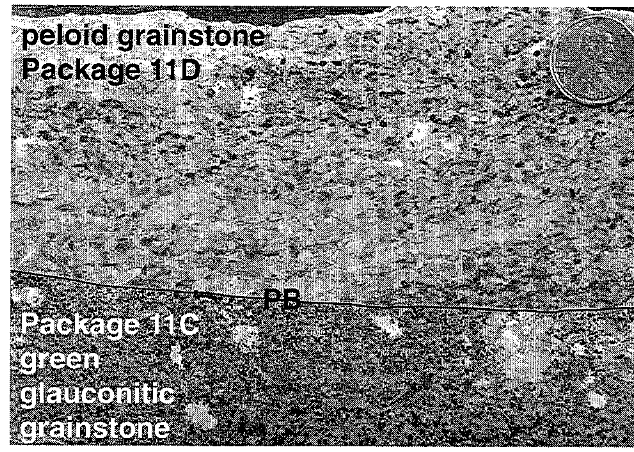


Figure 55. Planar truncation surface forms package boundary (PB) between Packages 11C and 11D, 16 ft (4.9 m) below top of San Saba Member of Wilberns Formation, Central Texas. PB (emphasized by black line) truncates burrows at 154 feet in Lange Ranch section. Scale is U.S. penny, 0.75 inch (19 mm) across. Compare with Figure 52.

C. angulatus Zone; this entire package is within the *Symphysurina bulbosa* Subzone.

Package 11D is clearly recognizable in the Lange Ranch section, Texas. The base is at the truncation surface on top of the green limestone bed at the top of Package 11C (Fig. 55). The brief drop in sea level at the top of Package 11D is at an increase in quartz sand content near the top of the Wilberns Formation (Fig. 14). Sand increases by a factor of 14 to 24 relative to samples 1 ft (30 cm) below and above. This sandy level is 10 ft (3.0 m) above the base of the *C. angulatus* Zone (Fig. 52).

This general interval of strata was identified as the Black Mountain Eustatic Event by Miller (1984), based on its recognition at Lange Ranch (top of Wilberns Formation), at the Chandler Creek section, Oklahoma (top of Signal Mountain Limestone), and at the Black Mountain section, Australia. Nicoll et al. (1992) later specifically identified this event at Black Mountain and showed its position in the lower part of the range of *Cordylodus angulatus*. Herein, we identify the Black Mountain Eustatic Event of Miller (1984) as the boundary between Packages 11D and 11E (Fig. 52). This event now appears to be of very brief duration.

Package 11E—Deepening and Shallowing

Package 11E is in the upper part of the Stonehenge Transgression and is characterized by continued relative sea-level rise. The base of Package 11E is at a peak in quartz sand content, and the top is at the base of a thick interval characterized by especially high quartz sand content (Fig.

17). In general, the siliciclastic content is low to moderate. Package 11E is 61 ft (18.6 m) thick at Lawson Cove, 48 ft (14.6 m) at Section A, and 30 ft (9.1 m) at Lange Ranch, Texas. Lithologies at Lawson Cove include lime mudstone, laminated fine grainstone, and minor flat-pebble conglomerate. This package records an interval of strata deposited under generally shallow subtidal conditions that slowly shallowed upward. The base of Package 11E is at a relative rise of sea level that follows a brief drop of sea level (Black Mountain Eustatic Event). Accommodation increased in the lower part of the interval, as indicated by the generally low siliciclastic content. Sedimentation filled available accommodation in the upper part of the package, and siliciclastic content generally is higher in the upper part of Package 11E than in the lower part. Package 11E includes all but the lowest part of the *Cordylodus angulatus* Zone and is in the *Symphysurina bulbosa* Subzone.

The top of Package 11E at Lawson Cove coincides with a thick flat-pebble conglomerate with very large clasts (4 in/10 cm across) at 518 ft in the section description, which coincides with the base of the *Rossodus manitouensis* Zone. A similar flat-pebble conglomerate at Lava Dam North at 273 ft in the described section is also at the base of the *Rossodus manitouensis* Zone. At Drum Mountains the base of this zone is a bed of rusty brown grainstone with sand waves at the top (unit 18); wavelengths are 2–3 ft (0.6–0.9 m) and wave heights are ca. 3 inches (8 cm). In the Lange Ranch section the base of this zone coincides with stromatolite mounds that are ca. 30 ft (9.1 m) above the base of the Threadgill Member of the Tanyard Formation; these are the only stromatolites in the Tanyard in this section. Lateral to these mounds is a lens of coarse flat-pebble conglomerate. At this level the quartz sand content increases from 0.66 per mil below the stromatolites to 4.49 per mil at the stromatolite-conglomerate level, and then it is reduced in the next sample to 0.90 per mil. These changes take place in three samples spaced at 5 ft (1.5 m) intervals. None of these examples (changes in quartz sand content, coarse flat-pebble conglomerates, stromatolite mounds) is especially unusual by itself, but all occur at the base of the *Rossodus manitouensis* Zone. We interpret these features as recording a brief drop of sea level at the top of Package 11E. This event has not been previously recognized or named, as is the case with several similar event horizons within Sequence 11.

Package 11F—Highstand Sedimentation

The base of Package 11F is at the sharp increase in siliciclastics at the base of the *Rossodus manitouensis* Zone, and the package ends at the top of the Barn Canyon Member. This interval is the top part of the Stonehenge Transgression. Package 11F is 27 ft (8.2 m) thick at Lawson Cove, 36 ft (11.0 m) at Lava Dam North and Section A, and 45 ft (13.7 m) at Lange Ranch, Texas. The top of the package at the base of the Burnout Canyon Member coincides with a lithologic change and with another large increase in quartz sand.

Lithologies in Package 11F include gray skeletal grainstone, flat-pebble and intraclast conglomerate, laminated and cross-laminated fine grainstone, and some lime mudstone. At Lawson Cove a fine grainstone bed near the middle of the package has ripple marks with wavelengths of 10 inches (25 cm) and heights of 3 inches (8 cm). The quartz sand content of Package 11F is mostly very high and reaches 75 per mil, although overlying strata have even higher sand content (Fig. 17). These lithologic data indicate very shallow subtidal to peritidal conditions at the top of Sequence 11, when accommodation was nearly filled.

Package 11F is the top of the highstand portion of Sequence 11, and its upper strata are transitional with the Burnout Canyon Lowstand. Its position is comparable to Package 6B, which has high sand content in the lower Lawson Cove segment, and the position is similar to Sequence 9, which has high sand content in the middle Lawson Cove segment. These intervals are also at the tops of sequences and are transitional with overlying lowstand intervals.

This package is assigned to the top part of the *Symphysurina bulbosa* Subzone; the base of the overlying subzone is only 2 ft (0.6 m) above the top of Package 11F. This interval is assigned to the *Loxodus bransoni* Subzone of the thick *Rossodus manitouensis* Zone. The base of the package and base of the zone essentially coincide, and the top of its lower subzone is in the overlying package.

Package 11G—Lower Part of Burnout Canyon Lowstand

The Burnout Canyon Lowstand coincides with the Burnout Canyon Member of the House Limestone, but this member has two distinct divisions. We interpret the lower part to be regressive and recognize it as Package 11G; the upper part is Package 12A. We name these two packages the Burnout Canyon Lowstand. This lowstand probably correlates with the *Peltocare* Regressive Event, a period of regression identified in the upper Tremadocian Series of Europe by Erdtmann (1986). The base of Package 11G is the base of the Burnout Canyon Member, and it coincides with a major lithofacies shift. Package 11G is mostly rusty brown fine grainstone, coarse grainstone, flat-pebble conglomerate, minor lime mudstone that may be gray, and abundant white to brown to black nodular chert. The grainstone is typically laminated and has low-angle cross-stratification sets; many of the laminations are replaced by rusty brown chert (Fig. 56). Much of the nodular chert is similar

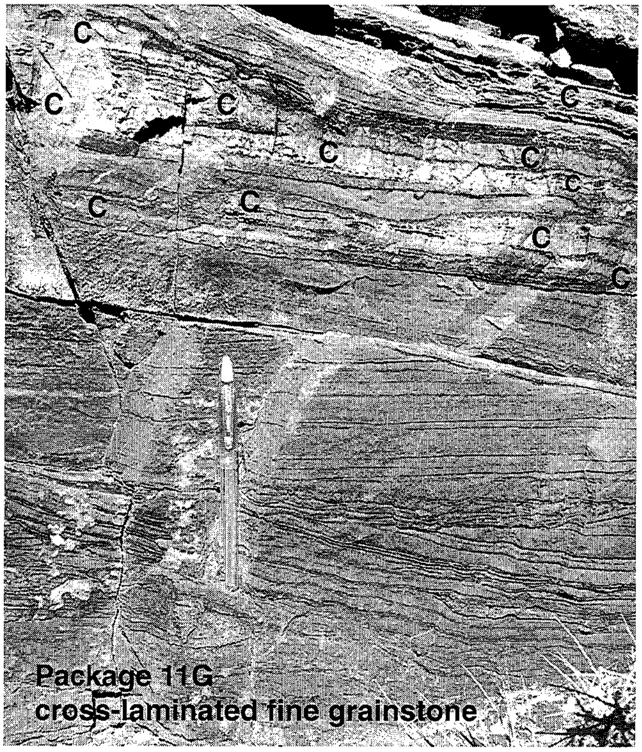


Figure 56. Brown cross-laminated fine grainstone and white to brown chert (C), typical lithologies of Package 11G in Burnout Canyon Member. Example is from Section A at 252 ft in described section (CD-ROM). Compare with similar white to brown chert shown on Figures 38,50,57. Scale shown by pen, 5.9 inches (15 cm) long.

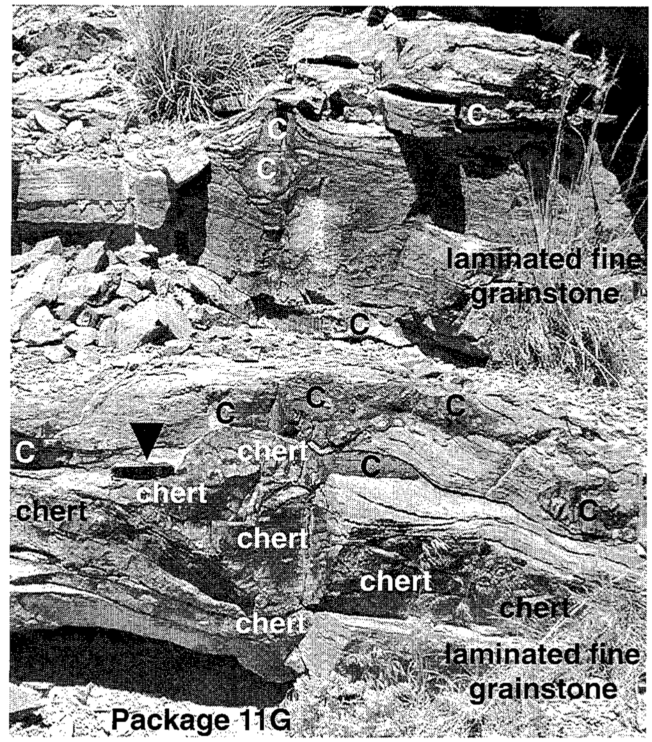


Figure 57. Vertically elongated white to brown chert nodules (C) cut across and disrupt brown laminated fine grainstone near base of Package 11G in Burnout Canyon Member. Example is from Section A at 234 ft in described section (CD-ROM). Compare with similar white to brown chert shown on Figures 38, 50, 57. Black arrow on left points to Swiss Army knife, 3.5 inches (9 cm) across.

to that in the lowstand strata of Package 10A, but some occurs as unusual vertically elongated nodules that cut across laminations in fine grainstone (Fig. 57). Package 11G ranges in thickness from 26 ft (7.9 m) at Lava Dam North to 20 ft (6.1 m) in the Drum Mountains.

Package 11G strata have abundant quartz sand that typically ranges from 70–100 per mil. The highest sand concentrations are mostly near the bottom of the succession. Much of the chert appears to be diagenetically recrystallized carbonate that was rich in quartz sand, including the chert nodules and the rusty brown lamination replacements. We interpret Package 11G as recording a tidal flat environment. The interval represents a prolonged interval of shallow sea level and reduced accommodation. The upper part of Package 11G has less quartz sand than the lower part, but the reduced quartz sand may be because the sandiest beds were recrystallized to chert. Figure 3 shows the sea level curve for Package 11G as a time of continuous relative sea-level drop. The top of Package 11G is placed where chert becomes 30–40 and sometimes 60 per cent of the strata and forms a brown cliff.

In the Lange Ranch section of Texas, Package 11G occurs below the middle of the Threadgill Member of the Tanyard Formation (Fig. 14). This interval has elevated amounts of quartz sand and includes the highest six samples for which insoluble residue data are available (Table 21).

The lower part of Package 11G is assigned to the *Loxodus bransoni* Subzone and the upper part to the *"Paltodus" spurius* Subzone of the *Rossodus manitouensis* Zone. All trilobite collections assigned to the *Symphysurina woosteri* Subzone of the *Symphysurina* Zone occur in the lower part of Package 11G.

SEQUENCE 12

Sequence 12 is a thick interval of strata that includes the upper part of the Burnout Canyon Member and all but the uppermost beds of the Red Canyon Member of the House Limestone. The base of the sequence is at the most regressive level in the Burnout Canyon Lowstand. The sequence includes lowstand strata at the base, but most of the sequence records subsequent relative sea-level rise, and the top of Sequence 12 is at the base of the next lowstand. Approximately half of the sequence is preserved at Lawson Cove, but the upper part was removed by Holocene erosion. Sequence 12 is 250 ft (76.2 m) thick and is best exposed at Lava Dam North. We studied only the base of this sequence at Section A, but from the description of Hintze (1951) we estimate the thickness of Sequence 12 as approximately 290–300 ft (88.4–91.4 m). Sequence 12 is divided into two packages.

Sequence 12 includes most of the thick *"Paltodus" spurius* Subzone of the *Rossodus manitouensis* Zone, although some older strata are also assigned to this subzone, as is Sequence 13. The top of Sequence 12 is somewhat below the top of this conodont zone and subzone. This interval is assigned to the *Symphysurina woosteri* Subzone of the *Symphysurina* Zone and to the *Bellefontia* Zone. The base of the *Paraplethopeltis* Zone is slightly above the top of Sequence 12.

Package 12A—Upper Part of Burnout Canyon Lowstand

Package 12A comprises the upper 60 percent of the Burnout Canyon Member and of the Burnout Canyon Lowstand. The base of Package 12A is at the base of a brown cliff-forming unit that is typically 30–40 percent and may be up to 60 percent chert. Varieties of chert include white to brown to black nodules, irregular vertical nodules that disrupt bedding, and some bedded chert. The top of the package is at a lithofacies shift that is the highest occurrence of such chert and is at the base of a slope-forming interval of gray limestone.

Package 12A weathers to a brown band that is clearly visible from a distance (Miller et al., 2001, Figs 5, 6), and this band was referred to by Hintze (1973) as the "brown marker bed" near the middle of the House Limestone. The color is from abundant brown silicification along joint-determined outcrop surfaces, from rusty silicification of brown grainstone laminae, and from the color of the nodular chert. Other lithologies include brown, laminated fine grainstone with cross-stratification sets and abundant quartz sand, flat-pebble conglomerate, minor gray limestone, and rare beds of quartz sandstone. We interpret these lithologies as a tidal flat facies. At Section A the base of Package 12A has interlaminated evaporites and silty sediment that we interpret as a supratidal deposit and as the most regressive part of the Burnout Canyon Lowstand. This evaporite unit is 1 ft (0.3 m) thick and occurs at the base of the cliff that comprises most of Package 12A.

Package 12A is 30 ft (9.1 m) thick at Lawson Cove, 38 ft (11.6 m) at Lava Dam North, 37 ft (11.3 m) at Section A, and 28 ft (8.5 m) at Drum Mountains. It may be recorded as the covered interval in the upper part of the Lange Ranch section, Texas (Fig. 17).

Package 12A is a small part of the *Loxodus bransoni* Subzone of the *Rossodus manitouensis* Zone, as is the upper part of the underlying Package 11F. No trilobites have been identified from Package 12A, but the interval is assigned to the *Symphysurina woosteri* Subzone of the *Symphysurina* Zone. The base of the subzone is in Package 11G, and taxa diagnostic of the overlying *Bellefontia* Zone occur slightly above the top of Package 12A. Based on present collections, it appears that the *S. woosteri* Subzone is confined essentially to the Burnout Canyon Member and to Packages 11G and 12A.

The Burnout Canyon Lowstand (Packages 11G and 12A) may not be preserved in many cratonic and platform stratigraphic successions except as an unconformity surface. Landing et al. (2003) described a widespread unconformity at the base of the *Rossodus manitouensis* Zone in New York and Vermont and showed that this zone rests on various older strata in different areas. Using sequence stratigraphy, the *R. manitouensis* Zone can be divided into three parts: 1) a thin interval (Package 11F) below the Burnout Canyon Lowstand, 2) a thin interval within the lowstand (Packages 11G and 12A), and 3) a thick interval above the lowstand (Package 12B). Where the *R. manitouensis* Zone rests unconformably on older strata, the likely interpretation is that subaerial erosion during the lowstand removed the thin lower part of the zone, and the zone is represented only by the upper part (Package 12B). In some depositional settings the *R. manitouensis* Zone rests on the *Cordylodus intermedius* Zone or *C. proavus* Zone (Landing et al., 2003), and this situation probably is also due to erosion during the Burnout Canyon Lowstand. However, such a large hiatus may include multiple periods of erosion that also occurred during the Drum Mountains Lowstand and the Basal House Lowstand. In areas with low rates of subsidence such as New York and Vermont, small hiatuses associated with these older lowstands may have become amalgamated into one large hiatus at the base of the *R. manitouensis* Zone. In contrast, rapid subsidence in the Ibex area produced accommodation that was sufficient to preserve a stratigraphic record of all of these lowstands.

Package 12B—Transgressive and Highstand Strata

Package 12B includes all but the highest beds of the Red Canyon Member of the House Limestone. The base of the package is at a lithofacies shift that coincides with a pronounced decrease in detrital quartz sand (Fig. 17). The top of the package is at another lithofacies shift that coincides with an increase in quartz sand. The complete package is present at Lava Dam North and is 212 ft (64.6 m) thick. Package 12A is also complete at Section A, but we have not studied the Red Canyon Member in that section. Package 12B is dominated by lime mudstone but includes lesser amounts of fine grainstone, skeletal grainstone, and flat-pebble conglomerate. Black chert occurs in small amounts, but at Lawson Cove chert occurs at several levels as vertical nodules that cut across lamination.

Many beds in Package 12B have abundant trilobite fragments that are silicified and weather out on bedding surfaces. The presence of silicified trilobites is probably due to the presence of quartz sand, which presumably is the source of silica for diagenetic replacement of fossils. Some samples near the middle of the package have elevated levels of insoluble residue (Fig. 17), but the material is silicified trilobite fragments rather than large amounts of detrital quartz sand.

Package 12B represents a lower energy, deeper environment than Package 12A. The decreasing amount of quartz sand is consistent with rising sea level (increasing accommodation and deposition of sand in more nearshore settings) in the lower part of the Red Canyon Member. Most of the package represents deposition below fair-weather wave base but above storm wave base, and deposition generally kept pace with accommodation.

All of Package 12B is within the thick *"Paltodus" spurius* Subzone and includes most of that subzone. Trilobites at Lawson Cove and Lava Dam North indicate that the base of Package 12B is only about 5–7 ft (1.5–2.1 m) below the base of the *Bellefontia* Zone. The base of the overlying *Paraplethopeltis* Zone occurs slightly below the top of the Red Canyon Member at Lava Dam North. This horizon is in the first bed above the top of Package 12B, so this package is essentially coincident with the *Bellefontia* Zone.

SEQUENCE 13

Sequence 13 is the highest and thinnest of our sequences in the House Limestone, and we have studied it only at Lava Dam North and the 1965 C section. The base is at an interval of lowstand strata near the top of the House Limestone (Fig. 58). Ross and Ross (1995, Fig. 1) placed the top of their third-order sequence at the House-Fillmore contact (Fig. 15 herein). We essentially agree with placement of a sequence boundary in this interval, but we place the top of Sequence 13 approximately 10.5 ft (3.2 m) higher (Figs. 3, 59). Sequence 13 includes the top 17 ft (5.2 m) of the House Limestone and the lower 10.5 ft (3.2 m) of the overlying Fillmore Formation, a total of 27.5 ft (8.4 m). The top of the Lava Dam North section is slightly above the top of the House Limestone, and only the basal 5 ft (0.3 m) of the Fillmore is preserved there. To clarify the House-Fillmore contact, we measured a short section through this interval slightly south of the 1965 C section of Hintze (1973). This short section and the 1965 C section

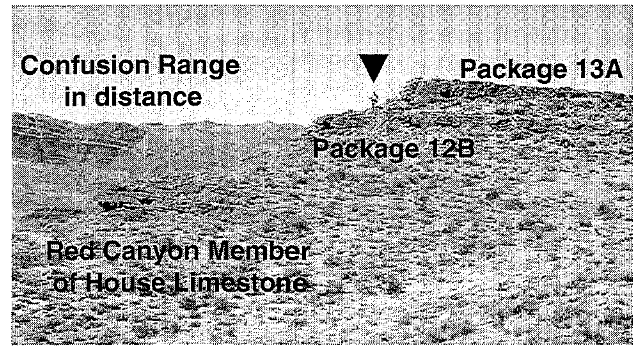


Figure 58. Upper strata of type section of Red Canyon Member of House Limestone at Lava Dam North section, southern House Range. All strata are assigned to Rossodus manitouensis *Zone. Most strata are assigned to Package 12B, which extends upward to near the feet of John Cutler (below arrow). He stands at field number 586, on unit 52 (CD-ROM), a laminated, dolomitic lime mudstone at the base of Package 13A and the top of the* Bellefontia *Zone. Highest visible strata are at field number 599, 6 ft (1.2 m) above base of* Leiostegium-Kainella *Zone and of Stairsian Stage. Lower 5 ft (1.5 m) of Fillmore Formation exposed slightly beyond top of upper ledge.*

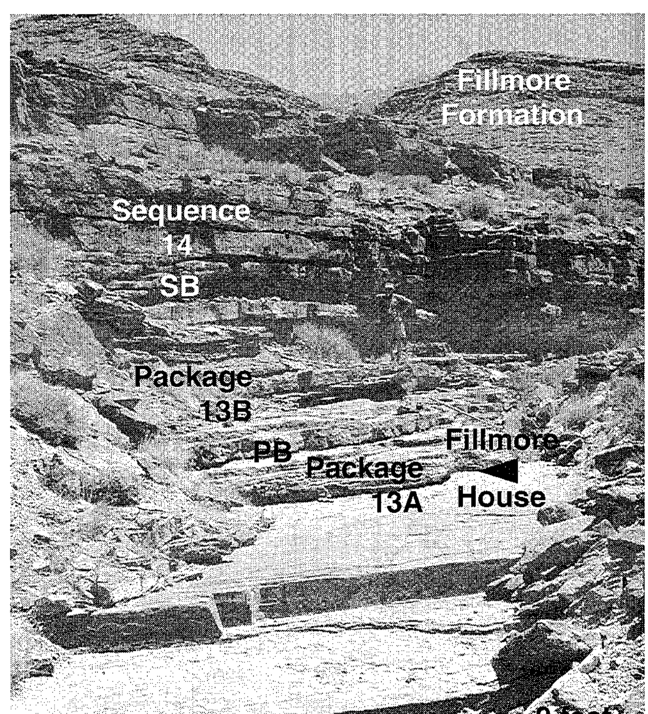


Figure 59. Base of 1965 C section, southern House Range. House-Fillmore contact, indicated by black arrow, is 1 ft (0.3 m) above base of section. PB = package boundary between Packages 13A and 13B, 2.5 ft (0.8 m) above zero mark of measured section (CD-ROM). Lars Holmer, at center of photo, indicates sequence boundary (SB) at base of Sequence 14, and base of Sauk IV internal, 11.5 ft (3.5 m) above zero mark. Base of Low Diversity Interval is near level of numeral 14.

are located about 2 miles (3.2 km) north of the Lava Dam North section. The description of these strata and our description of the lower 49 ft (14.9 m) of the Fillmore Formation at the 1965 C section are in the Appendix.

Sequence 13 includes two thin packages that form a transition between the House Limestone and Fillmore Formation. These strata record a distinctive shallowing event that we name the Tule Valley Lowstand because the Lava Dam North and 1965 C sections are located on the east margin of Tule Valley. These strata probably are present at the top of Section A, but we have not studied the upper half of that section.

Distinctive conodont and trilobite faunas characterize Sequence 13, which is slightly below the top of the thick *"Paltodus" spurius* Subzone. The upper part of Sequence 12 has a diverse, abundant conodont fauna that disappears at the base of Sequence 13 (Table 7, samples LDN 585.5 and 586). Some taxa reappear within Sequence 13, and they are joined by the lowest occurrences of *Chosonodina herfurthi, Variabiliconus transiapeticus, Drepanodus* sp. aff. *D. basiovalis* (Sergeeva) of Ethington and Clark (1981), and several taxa in open nomenclature (Figs. 10, 11). Conodont faunas of Sequence 13 have reduced diversity and abundance compared with most of the *"Paltodus" spurius* Subzone, but the fauna is more diverse and abundant than that of the overlying Low Diversity Interval.

The base of Sequence 13 is the bed below the base of the *Paraplethopeltis* Zone, but the upper part is assigned to the *Leiostegium-Kainella* Zone. The base of the latter zone characterizes the base of the Stairsian Stage.

Package 13A—Lower Part of Tule Valley Lowstand

Package 13A comprises the top strata of the House Limestone and the lowermost two beds of the Fillmore Formation. Package 13A is the top 22 ft (6.7 m) of the exposed section at Lava Dam North, but the top is eroded away. In the 1965 C section of Hintze (1973), Package 13A includes the interval 0 to 2.5 ft (0 to 0.8 m), of which 1 ft (0.3 m) is uppermost House and 1.5 ft (0.5 m) is basal Fillmore. The complete thickness of Package 13A thus includes 17 ft (5.2 m) of uppermost House Limestone at Lava Dam North and 1.5 ft (0.5 m) of lowermost Fillmore at the 1965 C section, or 18.5 ft (5.6 m). This compares with the 22 ft (6.7 m) incomplete succession that is exposed at the top of Lava Dam North.

The base of Package 13A at Lava Dam North is a 1 ft (0.3 m) bed of brown, dolomitic, laminated mudstone and grainstone and a 2 ft (0.6 m) bed of flat-pebble conglomerate and skeletal grainstone with trilobites and calcitic brachiopods. Above these beds, the top of the House is a 10 to 12 ft (3 to 3.7 m) cliff with a very coarse flat-pebble conglomerate and grainstone at the base that grades upward into dark gray lime mudstone. This cliff is a distinctive topographic feature at the top of the House Limestone and can be identified from far away (Fig. 58; Miller et al., 2001, Fig 10). The break in slope at the top of this cliff is the top of the House Limestone, but dark mudstone continues into the base of the Fillmore and is included in Package 13A. At Lava Dam North the base of Package 13A has a nearly three-fold increase in quartz sand compared with the sample below, and the quartz sand decreases upward through the package (Fig. 17). We interpret Package 13A as recording a rapid drop in sea level (decrease in accommodation) at the base. We interpret the basal sandy laminated dolomite and flat-pebble conglomerate as tidal flat or supratidal deposits. The dark lime mudstone at the top of the package has relatively little sand and records lower energy conditions during a time of slightly increasing accommodation. Lingulid brachiopods ca. 1 cm long are common at LDN-606, and these suggest very shallow subtidal conditions. The top of Package 13A is at a lithofacies shift to much higher energy strata.

Package 13A has a distinctive but not entirely unique faunal character. The base of Package 13A is 1 ft (0.3 m) below the base of the *Paraplethopeltis* Zone, which is only 7 ft (2.1 m) thick. The remainder of Package 13A at Lava Dam North contain trilobites of the *Leiostegium-Kainella* Zone (Fig. 12). Package 13A is part of the *"Paltodus" spurius* Subzone and has the lowest occurrences of several conodont taxa (Fig. 10).

Package 13B—Upper Part of Tule Valley Lowstand

Package 13B is the upper part of the Tule Valley Lowstand and includes 9 ft (2.7 m) of the lower Fillmore in the 1965 C section (Fig. 59). The base of Package 13B is an ooid-intraclast grainstone with straight-crested, 2D sand waves that are overlain by a coquina of the calcitic brachiopod *Nanorthis hamburgensis.* Holocene erosion removed this unit of strata at the top of the Lava Dam North section. Other strata in the 1965 C section are lime mudstone and flat-pebble conglomerate beds, one of which fills channels cut into an underlying conglomerate near the top of Package 13B. The quartz sand content of the ooid grainstone is greater than underlying strata of Package 13A, but the next two samples from Package 13B have much lower sand content. Quartz sand increases at the top of this package and occurs as a thin sandstone bed at 11.5 ft in the measured section. We interpret Package 13B as recording an abrupt drop in sea level and attendant reduced accommodation at the level of the ooid grainstone, followed by a slight rise in sea level, with another relative sea-level fall at the top of Package 13B. The interval from 10 to 11.5 ft (3 to 3.4 m) at the 1965 C section is a thin sandstone and silty limestone that we interpret as maximum regression or lowest sea-level within the Tule Valley Lowstand and as the top of Sequence 13.

The biostratigraphy of Packages 13A and 13B is complex and interesting because faunal changes are related to the boundaries between packages. The entire interval contains conodonts diagnostic of the *Rossodus manitouensis* Zone. Several characteristic taxa of the *"Paltodus" spurius* Subzone disappeared or occur in greatly reduced numbers near the base of Package 13A at Lava Dam North. Some of these taxa reappeared in reduced numbers in the uppermost House Limestone and lowermost Fillmore Formation, and several new taxa appeared (Figs. 10, 11). Most of the remaining taxa that occurred abundantly through the thick *R. manitouensis* Zone disappeared just below the top of Package 13B, and two species disappeared a few feet higher (Fig. 11, Table 6). The two faunal turnovers are thus near the base and the top of Sequence 13, both of which are at times of relative sea-level drop (Fig. 3). Ethington et al. (1987, Fig. 8.3) reported a similar pattern from this interval at a section that is about halfway between Lava Dam North and the 1965 C section. Overlying strata of Sequence 14 have greatly reduced numbers and diversity of conodonts and are referred to the "Low Diversity Interval" of Ethington and Clark (1981).

Trilobites display a two-step faunal turnover within Sequence 13, but the pattern is somewhat different than for conodonts because both steps occur in Package 13A. The first step coincides with the first step in the conodont faunal turnover and is essentially at the base of Package 13A. *Bellefontia* disappeared at the base of Package 13A (Table 7 and Fig. 12 herein; Ethington et al., 1987, Fig. 8.3), and *Paraplethopeltis* appeared in the next higher bed, in unit 52 at Lava Dam North. Our collections from Lava Dam North demonstrate an overlap between the lowest occurrences of trilobites diagnostic of the *Leiostegium-Kainella* Zone and the highest occurrence of *Paraplethopeltis* (Fig. 12). The extinction of *Paraplethopeltis* is the second step in the trilobite faunal turnover, and it occurs in the top beds of the House Limestone in Package 13A. The faunal turnover among conodonts and trilobites in Sequence 13 appears to be related to environmental changes associated with large-scale sea-level fluctuations.

Ethington et al. (1987) discussed the conodont extinction that occurs near the House-Fillmore contact in the Ibex area and also in strata of the Oklahoma aulacogen, where the extinction occurs near the McKenzie Hill-Cool Creek contact in the Arbuckle Group. Their Figure 8.5 shows ranges of conodonts across this formation contact in the Wichita Mountains and Arbuckle Mountains. The base of the Cool Creek is placed at the lowest occurrence of abundant quartz sand, siliceous ooids, and stromatolites. In Oklahoma they identified the same conodont extinction that occurs in the Ibex area at the top of Package 13B. This extinction occurs at a truncation surface that is between 2.1 and 2.4 m above the base of the Cool Creek in the Wichita Mountains. We correlate this truncation surface with a thin recessive sandstone seam at 11.5 ft (3.5 m) in the 1965 C section. This level is 10.5 ft (3.2 m) above the base of the Fillmore Formation and is interpreted herein as the low point of sea level in this interval and equivalent to the third-order sequence boundary of Ross and Ross (1995). We interpret the Oklahoma truncation surface as being the same boundary. The surface probably formed by subaerial exposure combined with marine abrasion during the subsequent rise in sea level.

In the Arbuckle Mountains the same conodont extinction occurs at the base of the Cool Creek rather than slightly higher. Ethington et al. (1987, p. 119) noted the different positions of these extinction events relative to the base of the Cool Creek and concluded that the McKenzie Hill-Cool Creek contact is diachronous. We agree with their conclusion and correlate the base of the Cool Creek in the Arbuckle Mountains with the top of Package 13B in the Ibex area.

Sequence 13 probably correlates with the lower part of the *Ceratopyge* Recessive Event of Erdtmann (1986). Ji and Barnes (1993) also discussed the regression and conodont faunal turnover at this stratigraphic level. Löfgren et al. (2000) reported *Rossodus manitouensis* from the *Ceratopyge* Limestone at the Stora Bakor section in Sweden; this is the same stratigraphic unit for which Erdtmann (1986) named the *Ceratopyge* Recessive Event. Most conodonts in these Swedish strata are part of the North Atlantic Faunal Province, whereas *R. manitouensis* is a part of the North American Midcontinent Faunal Province. The two faunas have few taxa in common, but perhaps the drop in sea level during the regressive event, Sequence 13, resulted in changes in ocean currents that allowed this widespread species to extend its geographic range into Sweden. Continuation of this regressive event apparently coincided with the extinction of this widespread, long-ranging species, *R. manitouensis*, only slightly later. Löfgren et al. (2000) named *Variabiliconus transiapeticus* and showed that it occurs in the *Ceratopyge* Limestone in Sweden, and herein we report its occurrence in the Ibex area. We correlate the lower part of the *Ceratopyge* Limestone with the uppermost part of the *"Paltodus" spurius* Subzone in Utah based on the occurrence of *V. transiapeticus* and *R. manitouensis* in both areas.

The top of Sequence 13 is the top of the Sauk III interval.

SEQUENCE 14—BASE OF SAUK IV

For completeness of classification, we assign an unknown thickness of the Fillmore Formation above Sequence 13 to Sequence 14. The sequence stratigraphy of the Fillmore is being studied by Benjamin Dattilo and K. R. Evans (see Dattilo et al., 2001; Evans et al. 2001). The Tule Valley Lowstand extends well upward into Sequence 14, which we assign to the Sauk IV internal.

SUMMARY OF SEQUENCE STRATIGRAPHY

Uppermost Cambrian and lowermost Ordovician strata in the Ibex area are a very thick sequence of carbonates deposited during times of rapid subsidence. The succession is divided into fourteen sequences, and the evidence for recognizing these sequence boundaries is summarized on Figures 60 and 61. The stratigraphic distribution of photographs illustrating this evidence is summarized on Figure 62. Lithology, succession of different lithologies, concentration of quartz sand, stromatolite horizons, and truncation surfaces are some of the criteria used to recognize sequence boundaries, and some of these features are summarized on Figure 62.

These sequences are separated by several major intervals of lowstand deposition or by truncation surfaces that we interpret as sequence boundaries. Major lowstands include the Corset Spring Lowstand, Red Tops Lowstand, Lange Ranch Lowstand, Basal House Lowstand, Drum Mountains Lowstand, Burnout Canyon Lowstand, and Tule Valley Lowstand. Whereas some sequence boundaries may be correlated with conformable successions in basinward settings, lowstand intervals consistently can be correlated lithologically across western Utah and sometimes across the continent. Some lowstand deposits are expressed on outcrop as recessive weathering intervals, especially those with shale content. Other lowstand deposits with abundant quartz sand may be resistant to weathering, especially if the sand is recrystallized to chert.

Strata above the Corset Springs Lowstand and below the Red Tops Lowstand constitute a prolonged period of major relative sea-level rise within the Sauk III Transgression, followed by generally highstands of sea level on the continent during the Hellnmaria Highstand. In outcrop, highstand deposits commonly are massively bedded or are thick successions of cyclic carbonates. Typically, highstand intervals record relatively shallow-water deposition because in west central Utah, the carbonate factory essentially kept pace with increases in accommodation during this transgression and highstand. In contrast, central Texas experienced lower rates of accommodation compared with Utah, resulting in a stratigraphic succession there that has more truncation surfaces and missing packages of strata. Several packages recognized in Utah are entirely absent in central Texas (Fig. 14).

There is a close relationship between the evolutionary development of conodonts, trilobites, and brachiopods with the boundaries between sequences and smaller packages. Many but not all of the important faunal changes that are used to characterize biozone boundaries coincide with such intervals of accommodation change. Many of the sequences and smaller packages are so widely recognizable that they must reflect eustatic changes of sea level. The relationships of these sequences to the conodont and trilobite biozonation make it possible to recognize these sequence-stratigraphic units in many widespread areas.

RELATIONSHIP OF SEQUENCES TO CHRONOSTRATIGRAPHY

Several boundaries between sequences or smaller packages coincide with important chronostratigraphic boundaries, some of which are no longer used but have historical significance. The base of the Millardan Series and its Steptoean Stage are below the interval we studied. The base of the Franconian Stage is slightly below the base of Sequence 1. The base of the Sunwaptan Stage is at the base of Package 1C. The base of the Trempealeauan Stage is within Sequence 2. Packages 1C through 6B comprise the Sunwaptan Stage. The base of the Ibexian Series and its Skullrockian Stage are at the base of Package 6C. The base of the Canadian Series, as used by Stitt (1977), is at the base of Package 7B. The base of the traditional Tremadocian Series of the Acado-Baltic Faunal Province is at the base of Package 11C, based on the widespread occurrence of the trilobite *Jujuyaspis borealis* at that level. The boundary between the Skullrockian and Stairsian stages is within Package 13A. Packages 6C through part of Package 13A comprise the Skullrockian Stage. The base of the traditional Arenigian Series of the Acado-Baltic Faunal Province is somewhere within the Fillmore Formation, far above the interval discussed in this report.

ATTEMPTED CORRELATION TO GREEN POINT, NEWFOUNDLAND

J. F. Miller and K. R. Evans

The Green Point section in western Newfoundland, Canada was recently chosen as the global stratotype for the base of the Ordovician System (Cooper et al., 2001). The stratotype horizon is a point in the rock succession that was chosen so as to coincide with the lowest local occurrence of the conodont *Iapetognathus fluctivagus*, and the report defining the boundary horizon identifies a succession of conodont zones shown on a range chart by Cooper et al. (2001, Fig. 2); see Figure 63 herein. It is not possible to correlate Ibex strata with the Green Point section, but sequences and packages defined in the Ibex area can be correlated confidently with other areas, such as the Threadgill Creek and Lange Ranch sections in Texas. These cor-

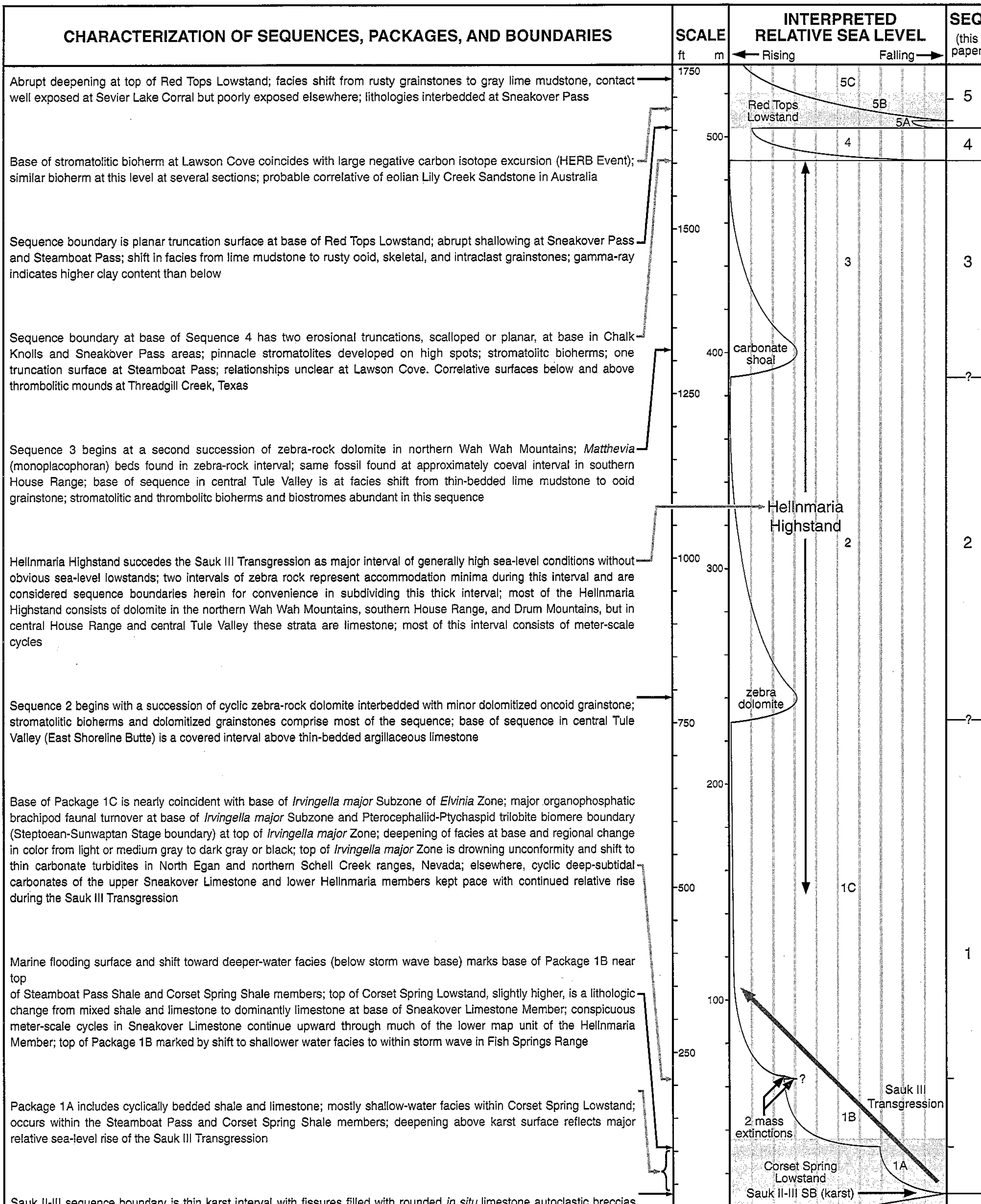


Figure 60. Summary of evidence for recognizing Sequences (SEQ.) 1–5, packages, boundaries, and other sequence stratigraphic features discussed in text. Sea-level curve from Figure 2. For similar summary of younger sequences, see Figure 61.

Sequence boundary at thin (1-2 inch [2.5-5.0 cm]) sandstone layer at 11.5 ft (3.5 m) at 1965 C Section; correlative truncation surface slightly above base of Cool Creek Limestone at Chandler Creek Section, Oklahoma; this horizon coincides with major conodont extinction in both sections at top of *Rossodus manitouensis* Zone

Package boundary at abrupt shallowing at 1965 C Section; influx of quartz sand coincident with facies shift from low-energy lime mudstone and peloid grainstone to high-energy ooid-intraclast grainstone with two-dimensional sand waves; brachiopod coquina of *Nanorthis hamburgensis* overlies sand waves; sand content decreases upward; Package 13A and 13B equivalent to *Ceratopyge* Regressive Event (CRE) in Norway

Sequence boundary marked by abrupt shallowing at base of Tule Valley Lowstand at Lava Dam North; distinctive laminated dolomitic mudstone at base coincident with quartz sand influx; overlying bed is thick flat-pebble conglomerate with abundant calcitic brachiopods (*Syntrophina* and *Nanorthis*) approximately at base of *Paraplethopeltis* Zone; sand content falls off rapidly as facies deepen upward; trilobite biomere boundary (base of *Leiostegium-Kainella* Zone) in middle of Package 13A; base of Fillmore Formation 3 ft (0.9 m) above biomere boundary near top of package

Gradual deepening and decrease in quartz sand above Burnout Canyon Lowstand; cratonward facies shift from high-energy tidal flat to shallow subtidal shelf sedimentation; Package 12B includes lime mudstone with interbedded intraclast or bioclast grainstones and flat-pebble conglomerates

Major influx of quartz sand marks base of Burnout Canyon Lowstand (equivalent to *Peltocare* Regressive Event [PRE] in Norway); sand content 10% near base, then decreases upward; abundant white chert, some vertical bodies; shift from storm-influenced subtidal carbonates to high-energy tidal-flat facies with low-angle cross stratification; Packages 11G and 12A weather reddish brown; base of Sequence 12 (regressive low point) has evaporite stringers at Section A

Increase in quartz sand in thick flat-pebble conglomerate bed at Lawson Cove; similar conglomerate at Lava Dam North; two-dimensional sand waves in grainstone at Drum Mountains; influx of quartz sand coincident with stromatolite mounds and flat-pebble conglomerate at Lange Ranch; all features coincide with base of *Rossodus manitouensis* Zone

Decrease in sand content within package 11D; abrupt influx of quartz sand at top of package at Lawson Cove and Lange Ranch marks Black Mountain Eustatic Event (BMEE)

Base of Tremadocian Series; base of Package 11C is widespread sandy brown bioclast-intraclast grainstone marker bed containing *Jujuyaspis,* found in all Ibex sections; package is sand rich; sand content increases to peak at package top; correlative brown shale with *Anisograptus* at Lava Dam North; glauconitic carbonate grainstone truncated at equivalent horizon (top of package) at Lange Ranch

Complex truncation surface at Section A; planar truncation at Lawson Cove; abrupt increase in quartz sand above truncation; round-clast conglomerate at base of Package 11B at Lange Ranch contains reworked *Clavohamulus hintzei* from Package 10C; regression interpreted at this level at Black Mountain, Australia; this interval probably equivalent to *Acerocare* Regressive Event (ARE) described from northern Norway; peak of large positive carbon-isotope excursion slightly below top of Package 11B

Sequence boundary at base of Drum Mountains Lowstand is truncation surface at top of stromatolites at Lawson Cove; abrupt influx of quartz sand decreases upward in Package 11A at Lawson Cove; Packages 11A and 11B highly condensed in Drum Mountains Section; coeval unconformity at Lange Ranch where Package 11A is missing

Top of Basal House Lowstand; abrupt decrease in quartz sand and shift to deeper facies; thin stromatolite or thrombolite bed at base of Package 10C in Waw Wah Arch and House Range Embayment; Packages 10A and 10B condensed and consist of zebra-rock dolomite above chert-clast conglomerate in the Drum Mountains

Abrupt increase in quartz sand at Lawson Cove and Lange Ranch; Packages 9B and 10A missing at Chalk Knolls South and Drum Mountains; unconformity in Drum Mountains on south flank of Tooele Arch indicates local tectonic movement; microkarst surface at Main Elk Creek Section in Colorado on west flank of Transcontinental Arch

Sequence boundary at top of *Symphysurina* coquina is base of House Limestone; major basinward shift of tidal flat facies and influx of abundant quartz sand partly recrystallized as white chert at base of Basal House Lowstand; quartz sand decreases upward in intertidal to shallow subtidal facies in Package 10A

Package boundary is planar truncation surface on stromatolites at Sevier Lake Corral north to Section A; influx of quartz sand decreasing upward within Package 9B at Lawson Cove; top of package is *Symphysurina* coquina; Package 9B is missing at Chalk Knolls South

Sequence boundary is planar truncation surface on microbial bioherm at Lawson Cove; thick succession of stromatolites in overlying strata in House Range Embayment nine times thicker than Lawson Cove; package 9A laps onto craton resulting in only carbonate strata in type section of Deadwood Formation in South Dakota

Rapid increase in accommodation above Lange Ranch Lowstand; deposition of massive thromobilitic bioherms or associated facies at Lawson Cove and in House Range Embayment; no microbialites at Lava Dam or Sevier Lake Corral

Sequence boundary is truncation surface at top of Lawson Cove Bed; sand-filled grikes at Sevier Lake Corral; overlain by widespread flat-pebble conglomerate and grainstone with common calcitic brachiopods (*Apheoorthis, Glyptotrophia, Nanorthis,* and *Syntrophina*); increase in fine quartz sand in grainstone; at Lange Ranch, complex truncation surface at top of erosional pedestals is locally base of Canadian Series

Quartz sand recrystallized to laterally persistent white chert marker bed overlain by widespread flat-pebble conglomerate and stromatolitic bioherm (Lawson Cove Bed); Package 7C preserved as thin erosional remnants (pedestals) at Lange Ranch and as 15-inch (38 cm) interval at nearby Welge Ranch Section

Base Canadian Series; faunal turnover in trilobites at base of Symphysurid Biomere; influx of 10% fine quartz sand at Lawson Cove with sand content decreasing upward; facies deepen upward; package 7B missing at Lange Ranch but present at Bluff Creek Section, Texas

Sequence boundary at base of Tank Canyon Bed (ooid grainstone); iron-stained truncation surface at Sevier Lake Corral; siliciclastic content decreases upward; at Lange Ranch, fresh-water carbonate cement and discoloration of conodonts below correlative truncation surface is due to weathering of conodonts during subaerial exposure

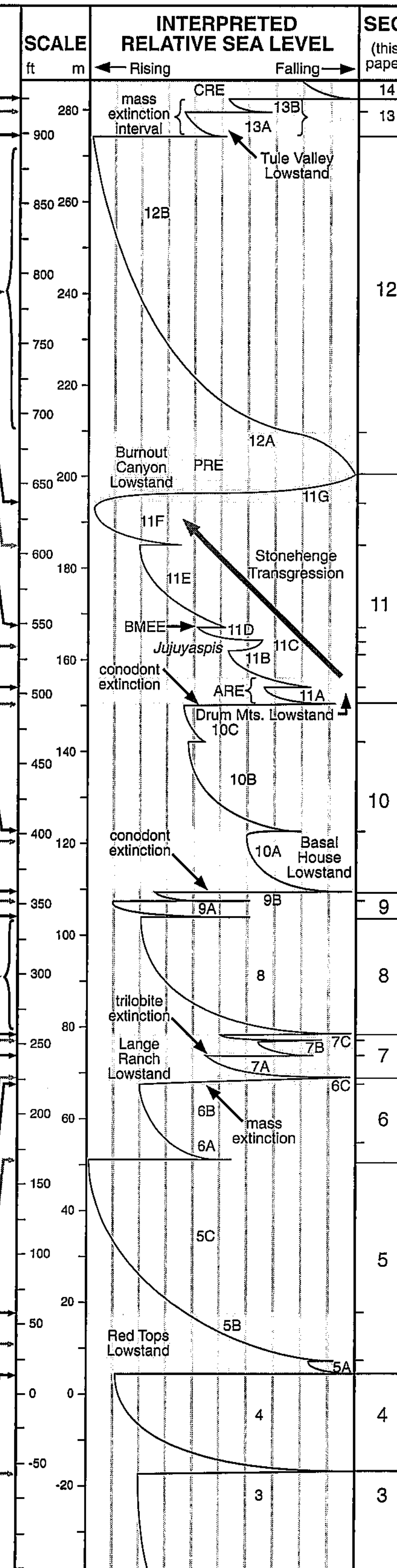
Base Ibexian Series; major conodont and trilobite faunal turnover; influx of silt and clay at base of Lange Ranch Lowstand; shallowing to base of Tank Canyon Bed

Sequence boundary, shallowing and deposition of red-stained intraclast conglomerate at Lawson Cove; fine sand in insoluble residues; contact poorly exposed elsewhere in Utah; truncation surface in Lange Ranch Section, Texas

Abrupt deepening at top of Red Tops Lowstand; facies shift from rusty grainstones to gray lime mudstone, contact well exposed at Sevier Lake Corral but poorly exposed elsewhere; lithologies interbedded at Sneakover Pass

Base of stromatolitic bioherm at Lawson Cove coincides with large negative carbon isotope excursion (HERB Event); similar bioherm at this level at several sections; probable correlative of Lily Creek Sandstone in Australia

Sequence boundary is planar truncation surface at base of Red Tops Lowstand; abrupt shallowing at Sneakover Pass and Steamboat Pass; shift in facies from lime mudstone to rusty ooid, skeletal, and intraclast grainstones; gamma-ray indicates higher clay content than below



relations utilize precise biostratigraphy based on the similarity of ranges of conodont and trilobite taxa in Utah and Texas.

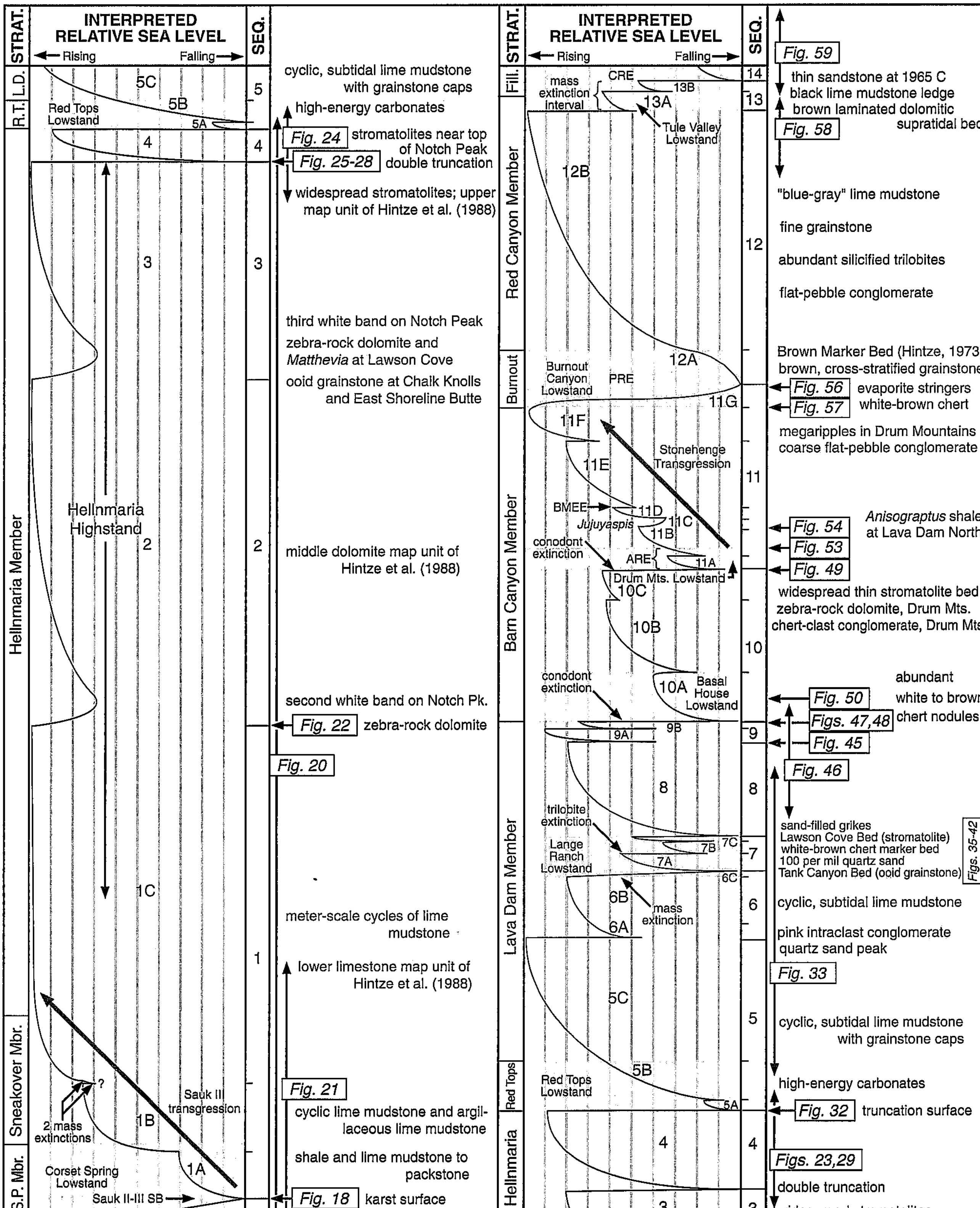
Many conodont species that occur in Utah also occur in the Green Point section, and ranges of species that occur in both sections are shown for comparison on Figure 63. The order of species at Lawson Cove is shown in ascending order of lowest occurrence, and the ranges of the same species are shown in the same order at Green Point. For Green Point, the only taxa that do not occur at Lawson Cove and thus are not included on Figure 63 are *Drepanoistodus* sp., *Iapetognathus* sp. undet., and *Cordylodus caboti* Bagnoli, Barnes, and Stevens 1987, which is a junior synonym of *Cordylodus intermedius* Furnish 1938. Many taxa recorded from Lawson Cove are not present at Green Point and thus are not shown on Figure 63.

The zones of Cooper et al. (2001, Fig. 2) are shown on Figure 63, but their zonation is problematic. Their *Cordylodus intermedius* Zone contains taxa that are diagnostic of the Upper Subzone of the *Cordylodus lindstromi* s. l. Zone and of the lower part of the *Cordylodus proavus* Zone. The *C. lindstromi* Zone is recognized worldwide, but it is not recognized in the Green Point section, which is intended to be a global standard for the base of the Ordovician System. The *Iapetognathus fluctivagus* Zone at Green Point contains taxa that are diagnostic of and confined to the *Cordylodus proavus* Zone (*Clavohamulus elongatus, Cordylodus hastatus*). The *I. fluctivagus* Zone at Green Point also contains taxa that are diagnostic of and confined to the *Cordylodus intermedius* Zone or slightly older strata at Lawson Cove and other areas (*Clavohamulus hintzei, Hirsutodontus simplex, Monocostodus sevierensis, Utahconus utahensis*). These taxa do not occur in the *Cordylodus intermedius* Zone at Green Point, but they do occur above that zone. Associations of taxa and ranges of taxa at Green Point are unique and cannot be reproduced in other parts of the world. Unique associations of taxa are common in other sections in the Cow Head Group (data tables in Barnes, 1988), and one cannot utilize faunal associations in one Cow Head section to correlate to other sections.

The same definitions of the conodont zones at Lawson Cove were applied to the ranges of taxa at Green Point, e.g., the base of the *Clavohamulus elongatus* Subzone is at the lowest occurrence of *C. elongatus*. The result of applying these definitions is shown on Figure 63 as an "Alternative Biozonation" to the zones of Cooper et al. (2001). The alternative biozonation cannot be compared with known records of conodont taxa anywhere else in the world. The alternative biozonation bears no resemblance to that of Cooper et al. (2001), and the faunal succession bears no resemblance to the succession at Lawson Cove nor to any section in the world. At Green Point, strata below Bed 19 yielded protoconodonts and paraconodonts, which are not useful for biostratigraphy, so there is no biozonation in strata below Bed 19. The lowest alternative zone is based on the lowest occurrence of *Cordylodus proavus*. The second alternative zone is based on the coincident lowest occurrences of *Cordylodus intermedius* and *C. prion*, which normally have lowest occurrences that are stratigraphically far apart (compare with Lawson Cove diagram). The third alternative zone is based on the lowest occurrence of *Cordylodus andresi*. At Lawson Cove this species characterizes the base of the *Hirsutodontus hirsutus* Subzone at the base of the *C. proavus* Zone. However, at Green Point *C. proavus* occurs much lower than *C. andresi*. The fourth alternative zone is based on coincident lowest occurrences of *C. lindstromi* s. l. and *Iapetognathus fluctivagus*, which characterize the bases of different zones at Lawson Cove. The fifth alternative zone is based on the occurrence of *Clavohamulus hintzei*, which occurs below both *C. lindstromi* s. l. and *Iapetognathus fluctivagus* at Lawson Cove. The sixth alternative zone is based on the lowest occurrence of *Hirsutodontus simplex*, which has a lowest occurrence below that of *C. hintzei* at Lawson Cove. The seventh alternative zone is based on the lowest occurrence of *Clavohamulus elongatus*, which occurs below *H. simplex, Clavohamulus hintzei, Cordylodus lindstromi, Iapetognathus fluctivagus*, and *Cordylodus prion* in a normal succession such as Lawson Cove. The last alternative zone is based on the lowest occurrence of *Cordylodus angulatus*, which overlies the zone based on *Clavohamulus elongatus*. It is clear that the conodont succession at Green Point is completely atypical, although it is supposed to serve as a standard for international correlation.

Green Point strata were deposited near the base of the continental slope and are a well known stratigraphic mélange. These strata include redeposited debris slide conglomerates, slump deposits, and distal turbidites, and these lithologies are interbedded with *in situ* shales (James and Stevens, 1986, description of Green Point section in Appendix). Considering the depositional environment at Green Point, the reason for the unusual conodont succession becomes simple to understand. Some or all of these conodonts are redeposited, they are out of order, and their ranges have been homogenized and extended by reworking the sediments in which they occur. Cooper et al. (2001, p. 22) stated that some taxa at Green Point may be reworked and recommended that some taxa should be used with caution for correlation. They suggested that species of *Cordy-*

Figure 61. Summary of evidence for recognizing Sequences (SEQ.) 3–14, packages, boundaries, and other sequence stratigraphic features discussed in text. Sea-level curve from Figure 3. For similar summary of older sequences, see Figure 60.


STRAT.
INTERPRETED RELATIVE SEA LEVEL
Rising
Falling
SEQ.
L.D.
R.T.
Hellnmaria Member
Sneakover Mbr.
S.P. Mbr.
5C
5B
5A
Red Tops Lowstand
4
3
Hellnmaria Highstand
2
1C
1B
1A
Sauk II transgression
2 mass extinctions
Corset Spring Lowstand
Sauk II-III SB
5
4
3
2
1
cyclic, subtidal lime mudstone with grainstone caps
high-energy carbonates
Fig. 24
stromatolites near top of Notch Peak
Fig. 25-28
double truncation
widespread stromatolites; upper map unit of Hintze et al. (1988)
third white band on Notch Peak
zebra-rock dolomite and Matthevia at Lawson Cove
ooid grainstone at Chalk Knolls and East Shoreline Butte
middle dolomite map unit of Hintze et al. (1988)
second white band on Notch Pk.
Fig. 22
zebra-rock dolomite
Fig. 20
meter-scale cycles of lime mudstone
lower limestone map unit of Hintze et al. (1988)
Fig. 21
cyclic lime mudstone and argillaceous lime mudstone
shale and lime mudstone to packstone
Fig. 18
karst surface
Fill.
Red Canyon Member
Burnout
Barn Canyon Member
Lava Dam Member
Red Tops
Hellnmaria
mass extinction interval
CRE
13B
13A
Tule Valley Lowstand
12B
12A
Burnout Canyon Lowstand
PRE
11G
11F
11E
Stonehenge Transgression
BMEE
11D
Jujuyaspis
11C
11B
conodont extinction
ARE
11A
Drum Mts. Lowstand
10C
10B
conodont extinction
10A
Basal House Lowstand
9A
9B
8
trilobite extinction
Lange Ranch Lowstand
7C
7B
7A
6C
6B
mass extinction
6A
5C
Red Tops Lowstand
5B
5A
4
3
14
13
12
11
10
9
8
7
6
5
4
3
Fig. 59
thin sandstone at 1965 C
black lime mudstone ledge
brown laminated dolomitic supratidal bed
Fig. 58
"blue-gray" lime mudstone
fine grainstone
abundant silicified trilobites
flat-pebble conglomerate
Brown Marker Bed (Hintze, 1973)
brown, cross-stratified grainstone
Fig. 56
evaporite stringers
Fig. 57
white-brown chert
megaripples in Drum Mountains
coarse flat-pebble conglomerate
Fig. 54
Anisograptus shale at Lava Dam North
Fig. 53
Fig. 49
widespread thin stromatolite bed
zebra-rock dolomite, Drum Mts.
chert-clast conglomerate, Drum Mts.
Fig. 50
abundant white to brown chert nodules
Figs. 47,48
Fig. 45
Fig. 46
sand-filled grikes
Lawson Cove Bed (stromatolite)
white-brown chert marker bed
100 per mil quartz sand
Tank Canyon Bed (ooid grainstone)
Figs. 35-42
cyclic, subtidal lime mudstone
pink intraclast conglomerate
quartz sand peak
Fig. 33
cyclic, subtidal lime mudstone with grainstone caps
high-energy carbonates
Fig. 32
truncation surface
Figs. 23,29
double truncation
widespread stromatolites

lodus and *Iapetognathus* should be used for correlation of the boundary horizon, but they did not explain how they decided which taxa should be considered to be *in situ* and which should be considered to be redeposited.

Analysis of the sedimentological characteristics of the strata at Green Point helps to identify intervals that may have redeposited fossils. Strata below Bed 19 are mostly shales that were deposited *in situ* on the continental slope; these shales contain a protoconodont-paraconodont biofacies, taxa that are not useful for biostratigraphy. Euconodonts that potentially could be used for biostratigraphy begin to occur in Bed 19, a coarse debris-slide conglomerate, but conodonts from such a conglomerate clearly are redeposited. Beds 20, 21, and the lower part of Bed 22 contain no euconodonts. James and Stevens (1986, p. 142) described these strata as shales and ribbon lime mudstones. Unit 23 includes shales interbedded with lime mudstone and thin lenses of grainstone containing quartz sand. Unit 24 is shale and parallel to cross-laminated siltstone. Unit 25 has a debris-slide conglomerate with 10 per cent quartz sand, and it has shales interbedded with limestones. In summary, Units 20 to 25 contain *in situ* deposits with admixed turbidites (grainstones with quartz sand, and parallel to cross-laminated siltstone) that increase in abundance upward. Conodonts from this interval are likely to be redeposited, and those from the conglomerate in Bed 25 certainly are redeposited. The slump deposit in Bed 27 was described by James and Stevens (1986, p. 142) as 4 m thick and extending along strike for 107 m. This unit clearly is not *in situ,* and conodonts from that unit certainly are redeposited. Samples reported by Barnes (1988) from shales in Beds 20–25 have typical taxa of the protoconodont-paraconodont biofacies, whereas limestones (including distal turbidite grainstones) have a euconodont biofacies that is typical of shallow marine environments (Miller, 1984).

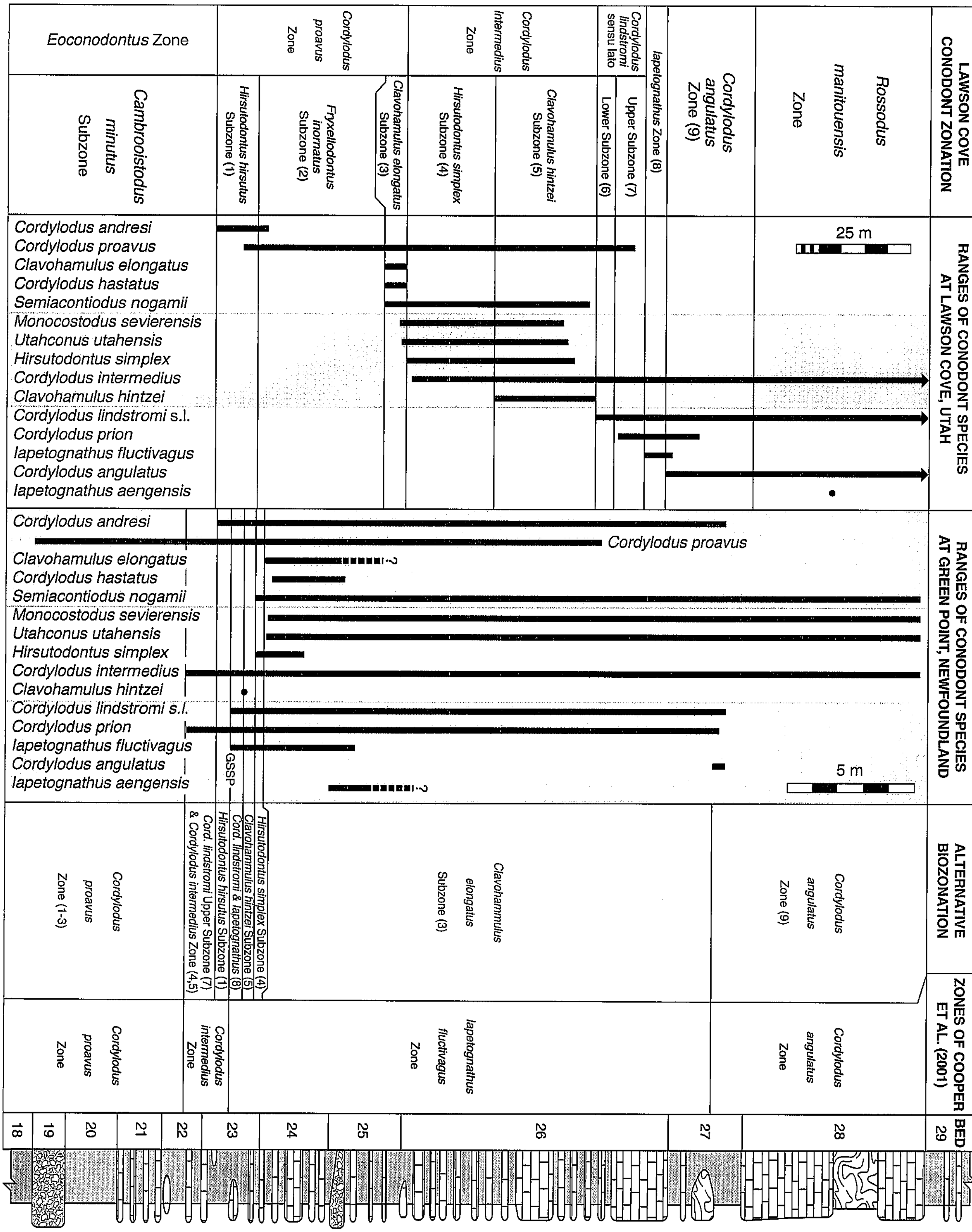
Although the homotaxial succession at Green Point is confused when compared with sections in other parts of the world, there is some order in the chaos. The homotaxial succession at Lawson Cove can be reproduced in many parts of the world, and the succession of subzones and zones on Figure 63 are numbered 1 to 9 for easy comparison. The same zones and subzones of the alternative biozonation at Green Point have the same numbers, but the numerical succession, in stratigraphic order, is 7, 1, 8, 5, 4, 3, and 9. The faunal succession is mixed, but the order is reversed (8, 5, 4, 3) in Beds 23–25. The conclusion is inescapable: this is an inverted homotaxial succession in which the oldest species are at the top, and the youngest species are at the bottom. So the succession of taxa at Green Point is not random, but it has been mixed up and is roughly upside-down. The interval where this faunal inversion occurs, Beds 23–25, is the same interval discussed above as having sedimentological characteristics that are compatible with redeposition of fossils. Near the top of the section is the lowest occurrence of *Cordylodus angulatus,* but those specimens are associated with the slump deposit in Bed 27 and cannot be considered to be *in situ.*

Figure 62. Stratigraphic distribution of photographs illustrating sequence stratigraphic units (SEQ.) and distribution of selected distinctive lithologic features discussed in text. Sea-level curves modified from Figures 2 and 3. Abbreviations of lithostratigraphic units (STRAT.) include: S.P. Mbr. = Steamboat Pass Shale Member, R.T. =Red Tops Member, L.D. = Lava Dam Member, Fill. = Fillmore Formation.

The designated boundary point for the base of the Ordovician System (GSSP on Green Point range chart, Fig. 63) is within an interval of strata that contains an inverted homotaxial succession of conodonts. Many conodont species in the Green Point section are the same ones that characterize the bases of zones and subzones in many parts of North America and on other continents, but their lowest occurrences and co-occurrences are unique to this section.

Such inverted successions are *prima facie* evidence of erosion, transport down a slope, and redeposition. Examples are known from inverted sequences of clast lithologies preserved in sedimentary basins after tectonic uplift of adjacent strata. In the geologic setting of Green Point, the inverted conodont succession must have formed during erosion and redeposition of shelf edge or upper slope strata that contained a normal homotaxial succession of shallow marine euconodont biofacies. The youngest shelf or slope strata were eroded first, and clasts as small as individual conodont elements were transported down the continental slope and redeposited. Such sediments and fossils formed the base of the inverted succession at the bottom of the continental slope at Green Point (Bed 19). Progressive erosion and redeposition of up-slope strata continued as clasts derived from older fossiliferous strata were transported down the slope and redeposited on top of the first redeposited sediments and fossils. Through time these sedimentary processes that operate normally in slope facies produced the inverted succession in Beds 22 to 25 (Fig. 63). Ranges of taxa were greatly extended by this reworking of conodonts, and this sedimentary homogenization produced associations of taxa never observed anywhere else except in the Cow Head Group.

Because of the inverted conodont succession at Green Point, it is impossible to correlate this global stratotype with strata from places that have a normal conodont succession. Redeposited fossils have very limited utility for biostratigraphic and chronostratigraphic correlation, and an inverted succession is even less useful. Cooper et al. (2001) proposed using the lowest occurrence of *Iapetognathus*


LAWSON COVE CONODONT ZONATION
Eoconodontus Zone
Cambrooistodus minutus Subzone
Cordylodus proavus Zone
Hirsutodontus hirsutus Subzone (1)
Fryxellodontus inornatus Subzone (2)
Clavohamulus elongatus Subzone (3)
Cordylodus intermedius Zone
Hirsutodontus simplex Subzone (4)
Clavohamulus hintzei Subzone (5)
Cordylodus lindstromi sensu lato
Lower Subzone (6)
Upper Subzone (7)
Iapetognathus Zone (8)
Cordylodus angulatus Zone (9)
Rossodus manitouensis Zone
RANGES OF CONODONT SPECIES AT LAWSON COVE, UTAH
25 m
Cordylodus andresi
Cordylodus proavus
Clavohamulus elongatus
Cordylodus hastatus
Semiacontiodus nogamii
Monocostodus sevierensis
Utahconus utahensis
Hirsutodontus simplex
Cordylodus intermedius
Clavohamulus hintzei
Cordylodus lindstromi s.l.
Cordylodus prion
Iapetognathus fluctivagus
Cordylodus angulatus
Iapetognathus aengensis
RANGES OF CONODONT SPECIES AT GREEN POINT, NEWFOUNDLAND
Cordylodus andresi
Cordylodus proavus
Clavohamulus elongatus
Cordylodus hastatus
Semiacontiodus nogamii
Monocostodus sevierensis
Utahconus utahensis
Hirsutodontus simplex
Cordylodus intermedius
Clavohamulus hintzei
Cordylodus lindstromi s.l.
Cordylodus prion
Iapetognathus fluctivagus
Cordylodus angulatus
Iapetognathus aengensis
GSSP
5 m
ALTERNATIVE BIOZONATION
Cordylodus proavus Zone (1-3)
Cord. lindstromi Upper Subzone (7) & Cordylodus intermedius Zone (4,5)
Hirsutodontus hirsutus Subzone (1)
Cord. lindstromi & Iapetognathus (8)
Clavohammulus hintzei Subzone (5)
Hirsutodontus simplex Subzone (4)
Clavohammulus elongatus Subzone (3)
Cordylodus angulatus Zone (9)
ZONES OF COOPER ET AL. (2001)
Cordylodus proavus Zone
Cordylodus intermedius Zone
Iapetognathus fluctivagus Zone
Cordylodus angulatus Zone
BED
18
19
20
21
22
23
24
25
26
27
28
29

fluctivagus to characterize the base of the Ordovician System, but that horizon is in an inverted succession of redeposited conodonts. One could argue that all of the other conodont taxa may be redeposited, but the *Iapetognathus* elements are *in situ.* Such an interpretation would have a diminishingly small probability of being correct, and it would not make the stratotype any more useful for correlation because other taxa can not be used for correlation. One could correlate the boundary horizon (GSSP) at Green Point to many different horizons at Lawson Cove, depending on which fossils one chooses to consider *in situ* versus redeposited. The only certain way of avoiding mistakes in correlation is not to use data from Green Point.

Other sections in the Cow Head Group show even more dramatic examples of redeposition of older taxa together with younger ones. The data tables of Barnes (1988) are most useful for finding these examples, however, because some taxa are not shown on his accompanying range charts. At the Broom Point North section in Newfoundland, for example, Barnes (1988, Table 2, Fig. 5) reported elements of *Proconodontus tenuiserratus, P. posterocostatus,* and *Cambrooistodus minutus* in sample 50 and above; these strata are at or above the lowest occurrence of Tremadocian planktic graptolites. All of these conodonts are much older than the base of the Tremadocian. None of those species occurs in strata above the base of the Ibexian Series, and some of these species do not even occur with one another in normal successions. Such homogenization of the ranges of taxa means that the Broom Point North section, like Green Point, has little value for correlation.

Miller and Flokstra (1999, Fig. 1G) showed that it is even impossible to correlate the Green Point section with the Broom Point North section, which was deposited in a shallower position on the same part of the continental slope as Green Point. Their figure is reproduced herein as Figure 64. It shows a graphic correlation between Green Point and Broom Point North using conodont data published by Barnes (1988). The line of correlation is unusual because part of it is horizontal, indicating that an interval of strata at Broom Point North correlates to essentially a horizon at Green Point. The "horizon" in the Green Point section is the 3–4 m interval that contains the inverted faunal succession and the GSSP. The line of correlation on Figure 64G changes from horizontal to vertical at the level of a thick debris-slide conglomerate in the Broom Point North section (unit 86 of Barnes, 1988, Fig. 5). This debris slide records the last time that many conodont taxa were eroded from shallower levels on the shelf or upper slope, transported down the slope, and redeposited. On Figure 64G these taxa line up as a series of last occurrences on the graphic plot, and the vertical part of the line of correlation is controlled by these last occurrences. Other plots on Figure 64 indicate that using data from Green Point and graphically correlating to another sections results in a line of correlation with no slope. Graphic correlations with either a horizontal or vertical line of correlation indicate an unconformity, faulting, condensed sedimentation, or reworking *en masse.* The line of correlation that relates Green Point to nearby Broom Point North contains both horizontal and vertical line segments (Fig. 64G) and indicates a correlation that makes no sense geologically.

Figure 63. Comparison of conodont ranges and biostratigraphic assignments between Lawson Cove section and Green Point section, Newfoundland, Canada. Species shown are those present in both sections. Green Point data modified from Cooper et al. (2001, Fig. 2), whose zonation was used to characterize the Global Stratotype Section and Point (GSSP) for the base of the Ordovician System. Some Lawson Cove conodont zones and subzones are numbered from 1 to 9. "Alternative biozonation" of Green Point strata employs the same definitions of biozonal units used at Lawson Cove, and biozonal units have the same numbers. Conodont succession at Green Point is interpreted herein as consisting of mixed-age faunas that are redeposited, homogenized, and partly inverted. Debris-slide conglomerates occur in Beds 19 and 25. Large slump deposits occur in Beds 27 and 28. Thin limestones in Beds 22–25 include grainstones that are distal turbidites. Shaded intervals in lithologic column are shales. For lithologic details, see James and Stevens (1986, p. 142).

Other fossil groups are of little use for correlating the Green Point global stratotype with strata in the Ibex area. The Green Point section has only two beds with trilobites, and both beds are the redeposited debris slides in Beds 19 and 25. No brachiopods are reported at Green Point. The excellent graptolite succession at Green Point begins 4–5 meters above the designated boundary point, just above the debris slide in Bed 25. However, there is no meaningful biozonation based on any group of fossils that can be used to calibrate the age of strata between the boundary level (GSSP) and the lowest graptolites. There is one graptolite horizon known in the Ibex area, at the Lava Dam North section (unit 27). This collection is assigned to the third Ordovician graptolite zone of Cooper (1999), but it is of relatively little help in correlating the designated boundary horizon at Green Point. The lack of graptolites is a shortcoming of the Ibex sections, but they have a variety of other data that are useful for correlation in the same interval of strata (Fig. 52).

Problems with the Green Point section were pointed out at three international meetings by Miller et al. (1998a), Miller et al. (1998b), and Miller and Flokstra (1999). The section and boundary point were nevertheless recommended by the Subcommission on Ordovician Stratigraphy to the International Commission on Stratigraphy, who approved it in 2000 as the global stratotype for the base of

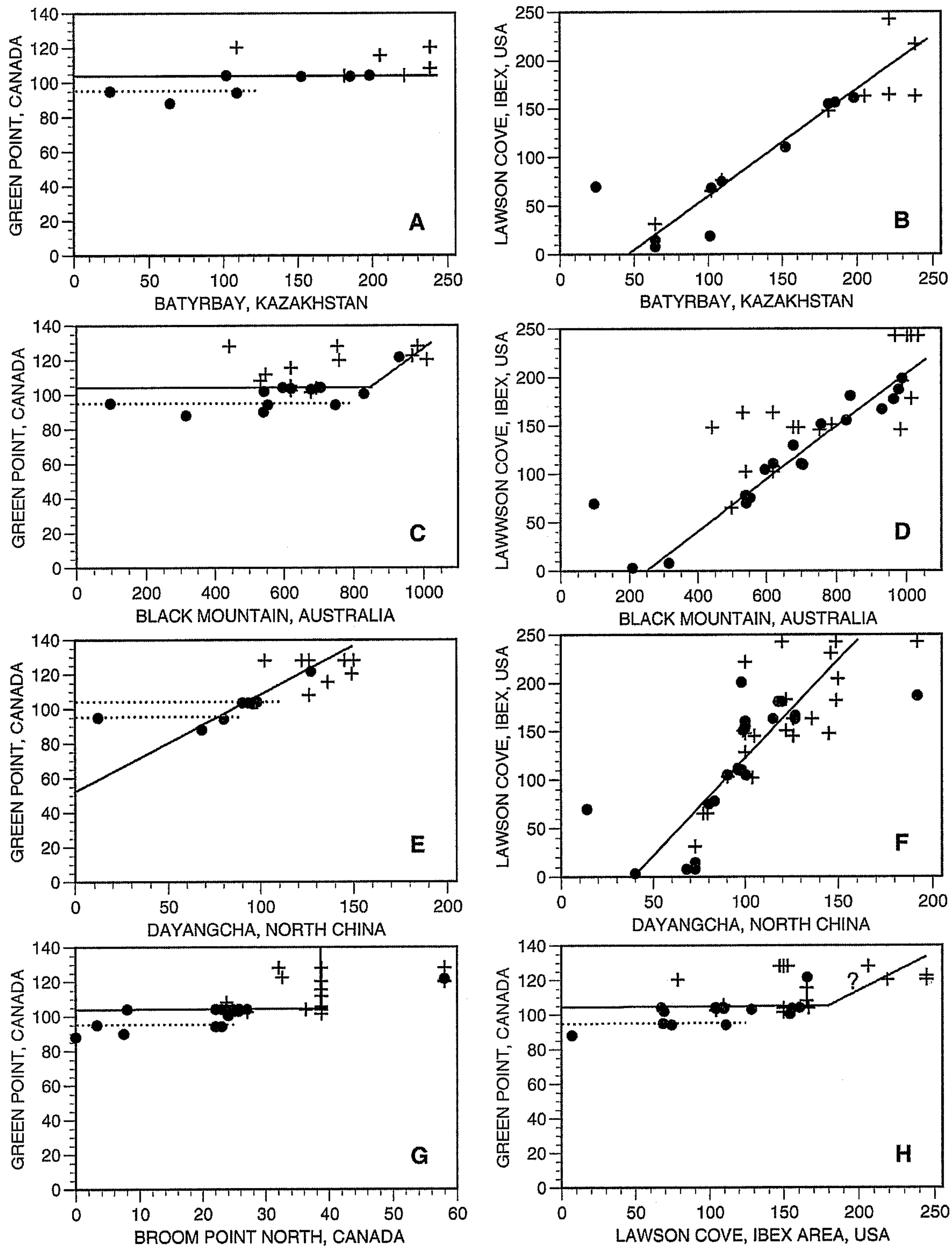


Figure 64. Graphic correlation plots for several important Cambrian-Ordovician boundary sections. Black circles indicate lowest occurrences of conodont species; crosses indicate highest occurrences of species. Solid lines are lines of correlation plotted by hand, not mathematically. Dotted lines emphasize other alignments of data points. Horizontal and vertical scales are not identical. Scales are in meters. Modified from Miller and Flokstra (1999, Fig. 1). Green Point data from Barnes (1988).

the Ordovician System. Because of its mixed and inverted conodont succession, lack of *in situ* trilobites, and lack of other fossils such as brachiopods, the usefulness of the Green Point section as a global standard is quite limited. The boundary point can not be correlated to the Lawson Cove section, nor to other sections in the Ibex area, nor to the Texas sections discussed herein, yet these sections have been documented in more detail than any other sections of comparable age in the world.

REGIONAL TECTONIC ELEMENTS AND SEDIMENTATION PATTERNS

K. R. Evans and J. F. Miller

The three local tectonic elements depicted on Figure 2—Tooele Arch, House Range Embayment, and Wah Wah Arch—extend nearly east to west, and measured sections discussed herein are located in all three tectonic features. The biostratigraphic and sequence stratigraphic units recognized herein can be traced through sections that form a nearly north to south transect that is approximately normal to these tectonic features. Changes in stratigraphic thickness among along these trends helps to delineate these tectonic elements and to document times of tectonic subsidence and uplift, or the dynamic response of sedimentation to changes across a block-faulted basement. These tectonic elements have been active since as early as the middle part of the Cambrian (Rees, 1985).

Studies of the Orr Formation (early Millardan Series, Steptoean Stage) show that the House Range Embayment affected both stratigraphic thickness and distribution of depositional facies (Evans, 1997; 1999). A 200 ft (61 m) interval of shallow-water carbonates, the Johns Wash Limestone Member of the Orr Formation, is restricted to the House Range Embayment and the south end of the Tooele Arch in the Fish Springs Range. The American Quasar Horse Heaven-State 16A well is located on the crest of the Confusion Range south of U.S. Highway 6-50; correlation of outcrop gamma-ray profiles with the gamma-ray log of that well indicates that the Johns Wash Limestone was deposited at least as far south as the northern part of the Wah Wah Arch. The Johns Wash Limestone is absent farther south, and its stratigraphic position is a thin interval of tidally influenced back-shoal carbonates in the middle of the Steamboat Pass Shale Member (Evans, 1997). Deposition of the Johns Wash Limestone essentially kept pace with subsidence and filled a major increase in accommodation during deposition of the *Dunderbergia* Zone in the House Range Embayment. This pattern of stratigraphic thinning on the Wah Wah Arch, thickening in the axial part of the House Range Embayment, and thinning on the Tooele Arch led Evans (1997) to interpret the underlying regional structure as block faults that formed the boundaries of a series of half grabens which affected the dispersal of sediments on the miogeocline (Fig. 65).

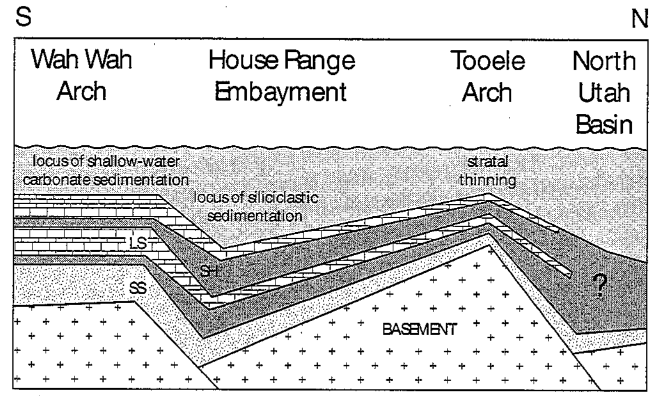


Figure 65. Major Cambrian-Ordovician tectonic elements affecting deposition of miogeoclinal strata in western Utah and eastern Nevada. Wah Wah Arch is a new term introduced in this report.

Lithofacies distribution also suggests that the House Range Embayment influenced deposition of the Hellnmaria Member of the Notch Peak Formation. The Hellnmaria in the Fish Springs Range (Hintze et al., 1988) and in the northern Drum Mountains (Dommer, 1980; Miller et al., 2001) is dolomite. Strata at the East Shoreline Butte, Chalk Knolls, and Sneakover Pass sections were all deposited in the House Range Embayment, and all are limestone. The lower Hellnmaria in the East Shoreline Butte section is quite dark and argillaceous, and these strata appear to represent a rather deep marine facies that was deposited in the House Range Embayment. The thickness of the Hellnmaria appears to be greatest in this section, but the thickness is unclear due to poor exposure and faulting. The thickness of the overlying Red Tops Member is also greatest in the House Range Embayment, at Sneakover Pass and Chalk Knolls South. The Red Tops is thinnest in the northern Drum Mountains and at Lawson Cove (Table 1), suggesting that the Tooele Arch and Wah Wah Arch had an effect on depositional thickness of that stratigraphic unit.

Variation in thickness of the Lava Dam Member is also related to these tectonic elements. The Lava Dam is thicker at Lawson Cove than at sections in the southern House Range (Table 1), but the thickness increases dramatically from Sevier Lake Corral to Sneakover Pass to Chalk Knolls South, and the Lava Dam Member is thin in the Drum Mountains section. The same pattern is shown more dramatically by tracing the thickness of Sequence 9 (uppermost Lava Dam Member) among the same sections. Figure 31 shows several trends within Sequence 9: 1) slow thickening northward across the Wah Wah Arch from Lawson Cove to Sevier Lake Corral, 2) more rapid thickening across the transition zone (Fig. 1) from Sevier Lake Corral to Tank Canyon to Sneakover Pass, 3) still more thickening going into the House Range Embayment at Chalk Knolls South, and 4) great thinning on the south flank of the Tooele Arch in the northern Drum Mountains.

Variation in thickness of sequences in the House Limestone indicates that a dramatic change in local tectonic activity occurred across the Notch Peak-House contact. Below this contact, strata thicken from Lawson Cove northward into the House Range Embayment and then become thinner on the south flank of the Tooele Arch. However, strata of Sequence 10 (bottom of House Limestone) are thickest at Lawson Cove and thin northward in a generally regular pattern (Fig. 31). In addition to this change in thickness, there is an unconformity at the Notch Peak-House contact at Chalk Knolls South and in the Drum Mountains. At Chalk Knolls South, Package 9B at the top of the Notch Peak Formation and Package 10A at the base of the House Limestone are missing at this unconformity. The same two packages are missing in the Drum Mountains, and the base of the House Limestone is a conglomerate with mostly chert clasts that are similar to the white to brown chert that is found in Package 10A farther south.

The provenance of the white to brown chert clasts is uncertain. Hintze et al. (1988, p. 28) described a section north of the Drum Mountains in the Fish Springs Range. They reported only rare chert in the lower House Limestone, so a northern source for the chert clasts is unlikely. Possibly the clasts were derived from chert deposited as part of Package 10A near or to the south of the Drum Mountains section. When Package 10A was eroded, the carbonate was dissolved, and the chert clasts were deposited during the succeeding marine transgression. The clasts commonly are as large as cobbles (Fig. 51), so it is unlikely that they were transported very far. We know of no other occurrences of this unusual conglomerate.

The Wah Wah Arch, House Range Embayment, and Tooele Arch are manifestations of the late Proterozoic breakup of Rodinia, when the margin of Laurentia formed during crustal extension (Fig. 65). The Wah Wah Arch and Tooele Arch are on the crests of tilted fault blocks, and the House Range Embayment was an area of greater subsidence; together they formed a half-graben-like structure. Recurring adjustment on these faults may have produced a monoclinal flexure that draped across the transition zone (near the Skull Rock Pass area) on the south margin of the House Range Embayment. These recurring adjustments produced more accommodation in this embayment, resulting in a thicker sedimentary succession during at least the Marjumian, Millardan, and lower Skullrockian (to top of Notch Peak Formation).

The geometry of the Johns Wash Limestone is typical of the influence of the House Range Embayment. It is thin in the Fish Springs Range (Fig. 1), suggesting that the Tooele Arch was conjoined with the House Range Embayment and that subsidence was greater toward its southern edge. The Red Tops Member also is quite thin in the Drum Mountains and is thick in the central House Range. Upward increase in siliciclastic content of the House Limestone, in the upper parts of Sequence 11 and in the Burnout Canyon Lowstand (Fig. 17), may be related to the influence of these structural elements. This increase in siliciclastic content continues upward into the Fillmore, which has considerable shale and silt admixed with limestones.

Two alternative hypotheses to explain the origin of these variations can be inferred from avalilable data. In one hypothesis, variations in stratigraphic thicknesses may be the result of pulses of uplift or subsidence along the boundaries between the Wah Wah Arch and the House Range Embayment combined with uplift on the Tooele Arch. In the second hypothesis, these variations may record dynamic sedimentation influenced by sea-level changes across the irregularly block-faulted basement. It is likely that a combination of these factors has influenced the preserved stratigraphic record.

APPENDIX

An extensive Appendix, consisting of data tables and descriptions of sections in PDF format, is on the enclosed CD-ROM. Tables 2–8 show identified fossils for sections at East Shoreline Butte, Chalk Knolls North, Lawson Cove, Lava Dam North, and 1965 C. Table 9 summarizes stratigraphic intervals assigned to conodont biostratigraphic units in all sections. Tables 10–21 show insoluble residue data, sequence or package assignments, and biozonal assignments for each sample in sections at East Shoreline Butte, parts of Notch Peak, Sneakover Pass, and 1965 C, Lawson Cove, Lava Dam North, Sevier Lake Corral, Tank Canyon, Section A, and Lange Ranch. Tables 22 and 23 show for all sections the stratigraphic intervals assigned to sequences and packages discussed herein. Captions for these tables are embedded in the table, and large tables have a sketch map showing how the pages fit together.

Descriptions are included for all Utah sections discussed in this report. Miller et al. (2001) published descriptions of sections at Lawson Cove, Steamboat Pass, Lava Dam Five, Lava Dam North, and Drum Mountains; these descriptions are reprinted herein.

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Benjamin Dattilo collected several conodont samples from the lower part of the 1965 C section and discussed sequence stratigraphy with Miller and Evans in the field. Tony Ekdale collected several conodont samples from the lower part of the Lawson Cove section. Jason Miller took some of the photographs used in this report. John Cooper discussed the sequence stratigraphy of Ibex area strata in the field with Miller and Evans. Michael Taylor worked cooperatively with Miller on the Notch Peak and House formations until his retirement from the U.S. Geological Survey. The 1996 Spring Vacation Field Trip class from Southwest Missouri State University helped J. F. Miller collect some trilobite and conodont samples from the Lawson Cove section. Lehi Hintze has assisted with and encouraged Miller's research in the Ibex area since 1965. Many professional and student geologists worked with Miller in the field since 1965, when his research in the Ibex area began.

Benjamin Dattilo and an anonymous reviewer read a preliminary draft of this report and made numerous suggestions that greatly improved the final manuscript.

Special thanks go to our late friend and co-author, Jim Stitt. Jim was diagnosed with cancer shortly after he attended the Seventh International Symposium on the Ordovician System at Las Vegas in 1995. He spent the next four years fighting for his life while continuing to teach and to complete his own research program. He completed several manuscripts that were co-authored with his graduate students; several are cited in the references. Despite the difficulties brought about by his health and by his preparing manuscripts, he agreed to help identify Ibex trilobite collections made by J. F. Miller and J. D. Loch. Most of these collections were prepared by Loch and identified by Stitt and Loch. Jim Stitt then prepared Plates 1 and 2 and wrote the portions of this report on trilobite biostratigraphy and on calcitic brachiopods in January 1999; revisions were made later by co-authors. As late as July 1999 Jim continued to identify trilobites and brachiopods for this report. As Summer faded to Fall, cancer finally took Jim's life. John Taylor (2000) wrote a memorial to Jim Stitt, his graduate advisor. We dedicate this report to the memory of James Harry Stitt.

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